高圧電定数を持つNb添加PZT薄膜を用いた圧電マイクロスキャナ

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論 文 内 容 要 旨

Micro optical scanners based on microelectromechanical systems (MEMS) technology are promising components due to its small size, high-speed operation and low production cost compared with the conventional scan modulus such as galvano scanner and polygon mirror. Among various applications of the micro scanner, endoscopic optical coherence tomography (E-OCT), which is a biomedical cross-sectional imaging method, is widely researched aiming for miniaturizing and simplifying the probing system for *in-vivo* imaging of hollow organs. Another application intensively studied is laser scanning display, including automotive head-up displays, head-worn displays and pico-projector. For the micro scanner used in these applications, wide scan angle, large mirror aperture and small chip size are commonly required. In order to meet them, the actuator of the scanner with large torque and small occupied volume is essential. The actuating mechanisms of the micro scanner are classified into four types; electrostatic, electromagnetic, electrothermal, and piezoelectric, and each of them has its own advantages and disadvantages. Among them, piezoelectric actuation with thin film lead zirconate titanate (PZT) is a promising candidate because of higher torque per input voltage than electrostatic actuators, smaller package size than electromagnetic actuators, and much shorter response time than electrothermal actuators. Moreover, the device can be integrated with stress sensors and frequency tuners without any significant change in the fabrication process.

Although several piezoelectric scanners using PZT thin films have been demonstrated for both E-OCT and laser display applications so far, further improvement in the optical scan angle is strongly desired for practical use. Enhancement in piezoelectric constants of PZT films is one of keys to improve the optical scan angle of the piezoelectric micro scanner, because it is the only way to push up actuation torques without any dimensional change in actuators.

It is well known that an addition of donor ions such as Nb^{5+}, Ta^{5+}, W^{6+} to PZT improves the piezoelectric constant due to facilitating domain wall rearrangement, and it has been widely practiced with bulk materials. For thin film PZT, at the same time, many researchers performed donor doping to achieve high performance for the MEMS application. However, to date, no literature has successfully demonstrated a doped PZT film with significantly higher piezoelectric constant than conventional non-doped PZT films. Moreover, there is no literature reporting the micro scanner using doped PZT thin film with high piezoelectric property.

In this work, we deposited Nb-doped PZT (PNZT) thin films by Rf magnetron sputtering method, and successfully achieved high piezoelectric properties suitable for MEMS actuators. Using obtained PNZT films, piezoelectric micro scanners that meet the requirements for E-OCT and laser scanning display were designed and fabricated. We demonstrated the superior scanning properties of the fabricated scanners compared to the device with conventional non-doped PZT films.

In Chapter 2, 12 at% Nb-doped PZT thin films were deposited on stainless steel and silicon substrates using RF-magnetron sputtering method with the aim of MEMS applications. The obtained films on both kinds of substrates had dense columnar structure and strongly oriented crystal structure. XRD measurement revealed that the dominant crystal orientations of the PNZT films differed depending on the kind of substrate, i.e. (001) direction of the tetragonal structure for stainless steel and (100) direction of the rhombohedral structure for silicon, respectively. The dependence of the crystal orientations on the substrate can be explained by the difference in the direction of the stress applied to the PNZT film during the phase transition after the deposition, resulting from the difference in the thermal expansion coefficients of the substrates. *P-E* hysteresis loops of the films on both kinds of substrates were shifted toward positive electric field, indicating the spontaneous polarization. This phenomenon allows us to omit the poling process after the deposition, and could be due to the defect dipoles at the PNZT/Ir interface stabilizing the ferroelectric domain with certain direction. The PNZT film on stainless steel substrate showed a square-shaped *P-E* hysteresis loop with a high remnant polarization P_r, whereas the film formed on silicon substrate showed a parallelogram-shaped hysteresis loop with a smaller P_r where polarization gradually increases to the saturation polarization P_{max}. Moreover, the dielectric constants of the films for the stainless steel substrate were approximately one third of that of the film on the silicon substrate. Such differences in ferroelectric properties are correlated with the amount of ferroelectric *a*-domain and *c*-domain in the film on each substrate. Resonance measurements of diaphragm structures with PNZT films found Young's modulus of the obtained film to be 49 GPa. Displacement measurements on both diaphragm structures resulted in piezoelectric coefficients of d_{31} = −217 pm/V for stainless steel substrate and d_{31} = −259 pm/V for silicon substrate. These values are more than 1.4 times larger than those of conventional non-doped PZT films, and quite close to that of PZT-5H ceramic which is widely used for piezoelectric actuators. These results indicate that the obtained PNZT films are suitable for the MEMS sensors and actuators.

In Chapter 3, resonant 1-D micro scanners actuated with a PNZT thin film were designed and fabricated for E-OCT applications. The device size is 3.4 mm × 2.5 mm or less, which is small enough to be installed in a side-imaging probe with an inner diameter of 4 mm. The scanners were designed to have resonance frequencies less than 125 Hz to obtain OCT images with a resolution of 200 pixels per frame or higher using a sweptwavelength laser source with a sweep frequency of 50 kHz. For higher sweep frequency available in the future, the scanners with higher resonance frequency were also prototyped. The measured resonance frequencies of the fabricated scanners ranged from 90.3 to 394 Hz, which agreed well with analytical calculation based on the Euler–Bernulli beams theory. All fabricated scanners achieved optical scan angles over 146° with driving voltage less than 1.3 V_{pp}. Using the scanners, a scan length of more than 5 mm can be achieved in a tubular probe with an external diameter of 5 mm by an extremely safe level of driving voltage for *in vivo* uses. Such an actuation performance was enabled by Nb doping in PZT, which made the scan angle more than double in comparison with nondoping case. Moreover, it was demonstrated that scanner with PNZT film show high optical scan angle without the poling process after the MEMS fabrication, whereas the device with PZT film need the poling to achieve enough high scan angles.

The OCT images of a human fingertip were acquired using the developed micro scanner. OCT images with sizes of 4.6 mm × 3 mm and 2.3 mm × 3 mm were obtained by the micro scanner placed 2.5 mm away from the object, and the fine structures in the human fingertip were clearly identified. This result suggests that the developed micro scanners are clinically useful for the E-OCT system. At present, the performance of the E-OCT system is mainly limited by the swept-wavelength laser source, and a higher frame rate and better scan stability are possible by the combination of a higher speed swept source and the micro scanners with scan frequencies as high as several hundred Hz. In addition, the PNZT-based-angle sensor was also developed for the feedback control of the micro scanner, and the sensitivity as high as 11~14 mV_{pp} deg^{-1} was demonstrated.

In Chapter 4, a non-resonant 2-D micro scanner actuated by a PNZT thin film was designed and fabricated for E-OCT application. The scanner has a gimbal-less structure with a large mirror aperture of 1 mm×1 mm, and the device size is 2.2 mm×2.7 mm which is small enough to be installed in a side-imaging probe with an inner diameter of 3.4 mm. The scanner was designed to have resonance frequencies greater than 1.37 kHz to achieve good response to triangle drive waveforms used in OCT imaging and high noise stability. The unimorph actuator with the PNZT film showed more than twice as large displacement as those with the non-doped PZT film, and also had superior linearity in the voltage response especially below 20 V_{pp}. These attractive properties of the PNZT film might be originated from ferroelectric domain motions facilitated by Nb doping. The non-resonant micro scanner with the PNZT actuators showed the optical scan angles of 18.6° for both scan axes with a drive voltage of 40 V_{pp} at low frequencies. These drive voltages are much lower than those needed for the static drive of electrostatic scanners. The internal energy consumption was less than 2.1 μW, which was significantly small compared to electrothermal or electromagnetic scanners. It is possible to enlarge the optical scan angle 2.5 times by reducing the thickness of the Si vibration plate within the acceptable level of the resonance frequency.

The scanning beam position measurement using a position sensor diode (PSD) revealed that the developed scanner showed good drive response to the 25 Hz triangle waves without any frequency filter. Although the operation with 50 Hz sawtooth waves caused ripples in the scan trajectory, the ripples were eliminated using a low pass filter removing harmonic components from the drive waveforms. The developed scanner is of practical use to achieve distortion-free 3-D OCT images with a frame rate of 50 fps in fast scan axis.

In Chapter 5, resonant 1-D micro scanners actuated by PNZT thin films were designed and fabricated for laser scanning display application. Designed scanners had a pair of the PNZT unimorph actuator placed around the 1.2 mmϕ mirror to apply the tilting torque to the mirror through the torsion bar. According to the results of the dynamic analysis using 2 DOF vibration model about the piezoelectric scanner, in-phase resonance mode, in which the mirror and the actuator move in phase, were selected for the scanning motion to achieve enough high mechanical-coupling gain keeping the device size small. The device areas of the scanners were less than 2.8 mm×2.9 mm, which was the smallest in the 1-D piezoelectric scanners to support SVGA resolution scanning displays. In order to extract high torque from the actuator, the drive electrodes on the PNZT film were electrically divided into two different parts according to the direction of the elastic stress induced in the PNZT film during in-phase resonance vibration, and voltage signals with opposite phase each other were applied to these two parts of the drive electrode. FEA calculation clarified that the actuator with divided electrode according to the stress direction showed 1.9 to 4.0 times higher displacements than those with undivided single electrode.

All fabricated scanners showed optical scan angles of 42.2°~85.2° at resonant frequencies of 23.7 kHz~30.8 kHz in atmospheric pressure, and driving voltages to achieve these performances were less than 14 V_{pp}. These scan performances are enough to support SVGA resolution scanned display. The scan performance of the device having the largest maximum optical scan angle is one of the highest in the 1-D micro scanner literature in terms of the product of mirror size D (1.2 mm) and optical scan angle θ(85.2°), i.e. $\theta \cdot D$=102 (deg.mm). In this device, the internal energy consumption was less than 1.5 mW, which was in the order of one hundredth of the electromagnetic scanners. In this work, dynamic deformation of the mirror is not within the scope. Further work will be needed to suppress the dynamic deformation into the desired regime i.e. below 10% of the utilized wavelength.

In conclusion, we can improve the optical scan angle of piezoelectric micro scanner by using a Nb-doped PZT thin film without any dimensional changes. The micro scanners with PNZT films can provide wide imaging area for both E-OCT and laser scanning display, which can strongly enhance the commercialization of these devices.

論文審査結果の要旨

微小なミラーをねじり振動させてレーザーを走査するマイクロスキャナは，ヘッドアップディスプレイ，ヘッドマウントディスプレイ，障害物検知センサ，距離画像測定装置などの幅広い用途がある。応用または光学的特性の観点から，限られたデバイス寸法の中で，大きなミラーを高速で大きく走査することが望まれるが，そのためにはミラーを駆動するアクチュエータに高い性能が求められる。駆動方式には，電磁方式，静電方式，および圧電方式があるが，小形化した際，体積当たりの駆動力という点で圧電駆動が有利である。しかし，高性能の圧電薄膜をSi基板に形成し，それをデバイスに加工することは必ずしも容易ではなく，そのことが圧電駆動方式のマイクロスキャナの実用化のための課題となっていた。

本論文は，上述のような現状と課題に対して，高圧電定数を持つNb添加チタン酸ジルコン酸鉛（PZT）薄膜をSi基板に堆積し，それを用いて，内視鏡光干渉断層計（OCT），およびレーザープロジェクタのためのマイクロスキャナを試作し，応用を踏まえて評価した成果をまとめたものであり，全編6章からなる。

第1章は序論であり，マイクロスキャナの応用と課題，PZT薄膜の圧電特性などを論じた後，本論文の目的を述べている。

第2章では，Nb添加PZT薄膜のスパッタ堆積と評価について述べている。ドナー不純物であるNbをPZTに12 wt%と従来になく高濃度に添加し，それがペロブスカイト結晶のBサイトに置換されると，圧電d定数が従来の高性能PZT（無添加）と比較して1.7倍に向上する。また，Nb添加によって，特定方向に分極し，分極反転しにくくなる結果，電圧印加範囲が広く取れること，また，ドメイン回転が促進され，圧電性能が上がるだけではなく線形性も向上することなどが見出された。これは有用かつ重要な成果である。

第3章では，内視鏡OCT用共振1軸マイクロスキャナの設計，試作，評価，およびOCTへの適用について述べている。この用途では，十分な視野を得るために，限られた大きさで非常に大きな走査角を要する上，生体内での安全上，駆動電圧を低くする必要がある。Nb添加PZTを用いることで，要求仕様を満たすマイクロスキャナを試作し，OCTシステムに組み込んで指表皮の断層像を得ている。これは有用かつ重要な成果である。

第4章では，内視鏡OCT用非共振2軸マイクロスキャナの設計，試作，および評価について述べている。平面内を均一に走査するためには，マイクロスキャナを三角波で2次元に駆動することが望まれるが，非共振駆動になるため，デバイス寸法と応答周波数に関する一定の制限の中で，大きな走査角を得ることは容易ではない。ここでは，高性能のNb添加PZT薄膜を用いることで，非共振駆動でも従来にない大きな走査角を得ることに成功している。これは有用かつ重要な成果である。

第5章では，レーザープロジェクタ用1軸マイクロスキャナの設計，試作，および評価について述べている。レーザープロジェクタでSVGA規格の高精細な動画を表示するためには，直径1 mm以上と大きなミラーを，約20 kHzの高速で30°程度以上の角度に渡って振動させる必要があるが，この要求仕様を満たすことは容易ではない。この用途でも，高性能Nb添加PZTを用いることで，従来のものと比べて高性能のマイクロスキャナを実現している。これは有用な成果である。

第6章は結論である。

以上要するに本論文は，従来にない高性能の圧電薄膜をPZTにNbを添加することで実現し，これを内視鏡OCT用共振マイクロスキャナ，同非共振マイクロスキャナ，およびレーザーディスプレイ用共振マイクロスキャナに応用し，各デバイスの設計，試作，および評価を総合的に行った結果をまとめたものであり，バイオロボティクスおよびバイオデバイス工学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。