Silicon Microfabrication and Vacuum Package of Scanning Mirror for Laser Display

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Silicon Microfabrication and Vacuum Package of Scanning Mirror for Laser Display
（レーザーディスプレイ用走査型ミラーのシリコン微細加工と真空パッケージ）

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論文内容要旨

Micromachined scanning mirrors are found in applications such as barcode scanner, optical communications and specially, potential applications in display by combining with solid-state laser sources. For display, one can use a two-axis mirror or two orthogonally placed one-axis mirrors. The requirements for laser scanning display are a large mirror-size scan-angle product and a high scan frequency. The mirror-size scan-angle product and scan frequency for the low resolution (QVGA) are 3.9 deg.mm and 8 kHz, respectively. Those for the high resolution (HTDV) are 23.3 deg.mm and 36 kHz, respectively. In spite of intensive research interests, the limitation of the micro-mirror driven electrostatically is the high operation voltage (~ 100 V) required for a large rotation angle at the high scan frequency (~ 15 kHz). This is due to the large stiffness of torsion hinge for the high scan frequency. In the case of magnetic actuators although the operation voltage is low, the power consumption (~ 50mW) by current is much larger than that of electrostatic actuator. Although, piezoelectric actuator generates a large force at low voltage, a high level of film deposition technology is needed for obtaining a good quality of piezoelectric effect.

Under the resonant scanning of micro-mirror, the mirror can be considered as a mechanical oscillator. The oscillation amplitude, which corresponds to the scan angle, is determined by the balance between input energy and loss. If the loss of oscillating mirror is decreased, the scan angle of the mirror increases. It is considered that the air friction generates a large loss since the friction boundary of the comb-drive mirror is long. Therefore, it can be expected that the operation of micro-mirror in vacuum improves the scan angle and the driving voltage. However, there are few reports on operation and characterization of micro-mirror for display in vacuum, although the air damping effect is investigated using a mirror at a low frequency. In order to use this advantage for mobile micro-mirror, vacuum packaging is a key technology. A micro-mirror was packaged in vacuum by anodic bonding. However, the obtained pressure was not low enough to remove the air friction completely since the pressure in the package was about 20 Pa and the mirror rotation angle was still increasing with the decrease of pressure.

The aim of this dissertation is to design, fabricate and package micro-mirror which satisfies requirements for application in laser scanning display. Therefore, the specifications of micro-mirror such as compact size, low cost, high resonant frequency for scanning horizontal axis, low resonant frequency for scanning vertical axis, low power consumption, and low operation voltage are considered.

In chapter 1 is an introduction. The research history, specifications, actuation methods and applications of micro-mirror are summarized. The problems are existing in the micro-miror and purpose of this dissertation is introduced in this chapter.

Chapter 2 investigates operation characteristics of 1-D comb-drive torsion micro-mirror in vacuum. Three types of micro-mirror are designed and fabricated by the SOI technology for studying operation characteristics in vacuum. The first type is a conventional comb-drive micro-mirror with the comb fingers installed on both sides of torsion bars. The second type is a micro-mirror with the slanted comb-drive structure. The third type is the same as the first type except the additional comb fingers installed on mirror plate. The effect of the increased comb number in the same micro-mirror structures is investigated. For all the three types, the optical rotation angles increase more than one order of magnitude with the decrease of pressure. The value of Q increases by about two orders of magnitude when compared with that in the atmospheric air. The operation voltage decreases by a factor more than 7 for the second type at the 24.5 kHz resonant frequency and the pressure of 7 Pa. The models for estimating the theoretical quality factor are presented and the results are compared with the experimental values at the low and high pressures.

Basing on the results investigated in chapter 2, the 1-D micro-mirrors are designed, fabricated and packaged in a high vacuum metal can, in which a die, a chip carrier and a non-evaporable getter are hermetically sealed. Individual die which is an array of the four micro-mirrors with a total size of 5.5 x 5.5 mm2 is diced from the SOI wafer by dry etching. The die is packaged in TO8 metal can with a window in a vacuum packaging machine at a pressure of 10^{-4} Pa. To evacuate the residual gases generated after the package process, a non-evaporable getter is used in the metal can. The resonant frequencies of the fabricated micro-mirrors are 13 kHz and 25 kHz, respectively. Optical rotation angle of about 10^{o} is achieved at a low driving voltage of 5 V. Due to the decrease of air friction loss, the operation voltage decreases by a factor of 32 compared with the voltage operated at atmospheric pressure. The operation pressure in the vacuum package is evaluated to be about 0.7 Pa from the amplitude and quality factor of mirror oscillation. This result demonstrates a solution for the problem of high operation voltage in air, which is inherent in the scanning mirrors with electrostatically driven vertical comb. A portable single MEMS scanner can be fabricated by the proposed vacuum packaging technology.

The theoretical approach models, vacuum operation characteristics and high vacuum package technology are presented for 1-D micro-mirror in chapters 2 and 3. However, for laser scanning display, a 2-D micro-mirror or two orthogonally placed 1-D micro-mirrors is required. The 2-D micro-mirror is preferred due to its compact. In addition, the electronic scheme in the 2-D micro-mirror is different from that of the 1-D micro-mirror. Therefore, a compact slanted comb 2-D micro-mirror scanner is the object of chapter 4, in which the advantages of slanted comb-drive actuator compared with rectangular comb-drive actuator are analyzed. The electronic isolation design and the differential driving method are also presented in this chapter. The angle magnified factor of slanted comb-drive actuator compared with rectangular comb-drive actuator is 1.6 times. The electrostatic torque of slant comb-drive is 1.2 times larger than that of the rectangular comb drive with similar dimensions. The natural frequency of the slant comb-drive mirror is decreased 20% compared with that of the rectangular comb-drive micro-mirror, which is useful for designing a 2-D micro-mirror having a gimbal frame of low resonant frequency. The linear relationship between driving voltage and rotation angle is experimentally obtained using the differential driving method, which is useful for controllable operation.

In chapter 5, vacuum operation characteristics of two-dimensional comb-drive micro-scanner are presented. Specially, the influence of air friction on the gimbal frame of 2-D comb-drive micro-scanner and the characteristics optimization between the high-frequency resonant mirror and the gimbal frame in vacuum are investigated experimentally and theoretically. The decrease of the resonant frequency for the gimbal frame is also effective to decrease operation voltage. The quality factor of the inner mirror having high resonant frequency increases faster than that of the gimbal frame having low resonant frequency when pressure decreases. The theoretical model based on air friction explains roughly the measured quality factors. The 2-D optical scanning angles about 10 degrees are demonstrated at the operation voltages around 10 V under vacuum conditions. The operation voltage for the inner mirror is smaller by a factor of 21 than that in the atmosphere. It is also shown that, even for the gimbal frame of 162 Hz resonant frequency, the operation voltage decreases by a factor of 3 when compared with that in atmosphere.

In chapter 6, the design, fabrication and package of 2-D micro-scanner in vacuum using the silicon-glass anodic bonding and the reflow of low-melting temperature metal are presented. The fabrication and package are high-field standard batch process using the SOI-based micromachining technology and the wet chemical etching of pyrex glass using the 0.5 μm Au/Cr protective mask layer in 49% HF solution. The packaged 2-D micro-scanner having horizontal and vertical resonant frequencies of 290 Hz and 30 kHz with the operation voltage of 12 V and 20V, respectively, is successfully demonstrated using proposed package method. The investigation of the squeeze air film damping causing by the package walls, the optical window and the substrate, shows that the distance between the package walls and the 2-D micro-scanner should be selected suitably for eliminating the squeeze air film damping.

In conclusion, the 1-D and 2-D comb-drive micro-mirrors were designed, fabricated and packaged in high vacuum using silicon microfabrication and high vacuum package technology using metal can and combing between anodic bonding and reflow of low-melting temperature metal. The direct approach models for analyzing air damping in the 1-D and 2-D comb-drive micro-mirror are introduced. The micro-mirror satisfying simultaneously requirements of high-speed scanning, high rotation angle and low operation voltage for laser scanning display have been realized in this thesis.

論文審査結果の要旨

マイクロミラーによりレーザー光を走査して画像を形成するレーザーディスプレイは，簡単な光学系で実現でき，半導体レーザーと組みわせることで極めて小型に構成できることより，実用化が期待されている。高解像度のディスプレイに要求される機械共振走査周波数は高いため，ミラーを支持するヒンジのばねを硬くする必要があり，また空気摩擦も大きくなると考えられる。このため，静電くし型アクチュエーターを用いたマイクロミラーでは，100V 以上の駆動電圧になることも稀ではなく，実用化を阻む要因の一つとなっている。本研究では，静電くし型アクチュエーターを用いたディスプレイ用 2 軸マイクロミラーの構造を最適化するとともに，真空パッケージにより空気摩擦を低減し，駆動電圧を低下させている。本論文は，これらの研究成果をまとめたものであり，全編 7 章からなる。

第 1 章は緒論であり，本研究の背景，目的および構成を述べている。

第 2 章では，静電くし型アクチュエーターを用いた 1 軸マイクロミラーの設計，製作と真空中の動作特性について述べている。3 種類の 1 軸マイクロミラーを設計，製作し，空気中および真空中における動作特性を測定している。ミラーの構造と動作特性の関係を理論的および実験的に調べ，駆動効率のよい構造を見出している。大気中の駆動に比べ 7Pa の圧力では，駆動電圧を 1/7 以下に低下できることを見出している。これらは有益な成果である。

第 3 章では，金属缶を用いたマイクロミラーの真空パッケージについて述べている。1 軸マイクロミラーをガラス窓のある金属缶に密閉封止している。内部圧力は約 0.7Pa で，空気摩擦の影響をほぼ完全に取り除き，6 週間の耐久試験において劣化が見られていない。真空パッケージにより 13kHz の共振周波数で 10 度の走査角を駆動電圧 5V で達成できたことは，高く評価される。

第 4 章では，静電くし型アクチュエーターを用いた 2 軸マイクロミラーの設計，製作および動作特性について述べている。1 軸はミラーの水平方向高速走査に，他の 1 軸はミラーを支えるジンバルフレームの垂直方向低速走査に用いられる。傾斜くし構造を提案することで，走査角を拡大し，共振周波数の低下を抑えている。また，2 軸静電くし型アクチュエーターの駆動に必要な複数の配線をＶ型ヒンジとシリコン層の分割を用いる比較的簡単な製作プロセスにより実現している。これらは有用な知見である。

第 5 章では，2 軸マイクロミラーの真空中動作特性について述べている。マイクロミラーおよびジンバルフレームに対する空気摩擦の影響を測定し，大気中に比べてミラーの駆動電圧を 1/21 に，ジンバルフレームの駆動電圧を 1/3 に低下できている。これらは有益な成果である。

第 6 章では，2 軸マイクロミラーのウエハレベル真空パッケージについて述べている。量産においてはウエハレベルのパッケージが有効である。ガラスとシリコンウエハの陽極接合により，2 軸マイクロミラーを真空に密閉封止している。脱ガスとゲッター活性化および封止が順次有効に行える低融点金属リフロープロセスを提案し，2 軸マイクロミラーの真空パッケージを達成していることは，重要な成果である。

第 7 章は結論である。

以上要するに本論文は，レーザーディスプレイのための静電くし型アククエーター駆動マイクロミラーを設計，製作し，空気摩擦の駆動電圧に対する影響を定量的に明らかにし，真空パッケージによる実用的な製作方法を提案したもので，ナノメカニクス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。