表面マイクロマシニング技術を用いた光スイッチ

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The MEMS (Micro-ElectroMechanical Systems)-based optical switches are attractive components for an OXC (Optical Cross-connector) router of WDM (Wavelength Division Multiplexing) optical communications in future networks. Optical MEMS, or MOEMS (Micro Optical ElectroMechanical Systems), is a promising technology to meet the optical switching need for large port-count high-capacity OXCs. The optical switches with micromirrors fabricated MEMS process can be good substitutions for large-scale OXC's due to its low electric power consumption and high reliability. Potential benefits of a MEMS-based optical switch include scalability, low loss, short switching time, low power consumption, low cross-talk and polarization effects, and independence of wavelength and bit-rate. There is also a large need for 1x2 or 2x2 switches, which are very often used with the larger fabrics as part of the protection network.

In this paper, the surface micromachined optical switch was successfully fabricated by newly developed processes for sidewall metallization and planarization, and anhydrous
HF GPE process for dry release.

For optical switching, it is designed a planar-type thermoelastic microactuator with lever mechanism for displacement amplification and a shallow arch-shaped leaf spring with a latch-up operation. Latch-up actuation is prerequisite to implement an optical switch with low power consumption and high reliability. The temperature and the principal stress distributions, the thermoelastic deformation, and the prediction of resonant frequencies of the microactuator are investigated. The buckling characterization of arch-shaped leaf spring with clamped ends is also analyzed. Resonant frequencies of the leaf spring according to its geometry variation are calculated. The active bar is the bending type in the cases of 1st and 2nd mode, the amplification bar moves to rotate as the central axis of two hinge parts in the 3rd mode. The proposed microactuators and arch-shaped leaf spring have advantages of easy assembly with other optical component by way of fiber alignment in the substrate plane.

In this paper, the surface micromachined optical switch was successfully fabricated by newly developed processes for sidewall metallization and planarization, and anhydrous HF GPE process for dry release.

The surface micromachining process is the basis for the fabrication of MEMS. One of the key processes in surface micromachining is the dry release of microstructures without subsequent sticking of these structures to the substrate. The sacrificial oxide is removed by newly developed anhydrous HF GPE process for the dry release of microstructures free of stiction. The developed GPE process with anhydrous HF gas and alcoholic vapor such as methanol, IPA was characterized and its selective etching properties were discussed. In silicon surface micromachining, anhydrous HF GPE process was verified as a very effective method for the dry release of microstructures.
It is successfully fabricated and characterized an optical switching device with no virtually process-induced stiction and no residues. The proposed process features simplicity, virtually no capillary forces and compatibility with conventional IC processes as well.

For the sidewall metallization of the optical switch with HAR (High-Aspect-Ratio) microstructures after Si deep RIE (Reactive Ion Etching), a novel lithography method was newly developed with the combination of Si deep RIE and negative DFR (Dry Film Resist) capping processes. The DFR as a capping sheet is to prevent the positive photoresist or the metal from entering into the extreme deep trench. To form the metal surface of vertical sidewall for optical switching applications, various metal films such as Au and Al are deposited by various evaporators. This is done by an evaporation, where the wafers are oriented in 45 degree direction. The newly developed novel lithography method will enable to patterning metal electrodes inside deep trench or metal reflectors onto sidewall for the fabrication of MEMS devices with HAR microstructures.

The sidewall planarization is also introduced to the improvement of reflectivity of micromirrors by KrF excimer laser annealing. In order to exhibit excellent performance of OXC, it is important to improve reflectivity of the micromirrors through the planarization of the sidewall with lots of scallops formed by Si deep RIE process. The reflow process of metal has been used to surface planarization because it is widely used in semiconductor industry for metallization process. The pulsed KrF excimer laser annealing has been applied for reflowing the aluminum thin film to obtain good reflectivity of the micromirror. The surface planarization has been achieved by the grain growth and agglomeration by the heat provided laser energy, which shows good
reflectance as above 98%. The surface roughness is reduced to about 10% level of initial stage. The reflectivity of the samples shows good characteristics the region of from 1300nm to 1550nm for above 200mJ/pulse. Therefore this reflow process induced laser annealing is a good candidate process for improving surface roughness and reflectivity of micromirrors using aluminum.

The planar thermoelastic microactuator with a latch-up operation for optical switching are designed and fabricated. The fabricated microactuator consists of four cantilever-shaped thermal actuators, four displacement linkages, two shallow arch-shaped leaf springs, a mobile shuttle mass with a micromirror, and four elastic boundaries. The actuation is incurred by the thermal expansion due to the current flow in the active polysilicon cantilever. This displacement of the actuator is amplified by lever mechanism, and transferred to the shuttle mass for the movement of micromirror. In order to evaluate the effectiveness of the thermal actuation, the microactuators such as polysilicon and SOI types are fabricated by using silicon surface micromachining. In the case of SOI type, the experimental amplified displacement of the microactuator and lever was more than 30µm at 20V (25mA) input voltage. The frequency response for square wave input was measured up to 90Hz. Then driving voltage in the forward moving is about 23V, but in the backward moving is about 15V because of the restoring force caused by internal stresses of buckling springs. The switching time is below 5 msec. It is also analyzed its snap-through characteristics for bi-stable operation, and found that the 3rd mode mainly contributed to its snap-through motion. To overcome the aging of the microactuator, it is necessary to find a method for vacuum packaging of optical switching device.

Silicon benches each of which has two V-grooves and two pits on it to fix optical fibers
and collimating ball lenses are fabricated on a (100)-silicon wafer using KOH wet etching. Optical alignment was easily implemented by locating two benches on two sides of a 2x2 switch device perpendicularly.

For the future work, it needs to find the vacuum packaging, optimize the structure for lower driving voltage, and test its reliability.

To overcome scallop phenomena and footing effects by Si deep RIE, it is proposed and fabricated LIGA (Lithographie Galvanformung Abformung) PMMA (polymethylmethacrylate) micromirror. It is investigated characteristics of polymer-based LIGA PMMA micromirror for MOEM optical switch application to WDM optical communication systems. After acid and release tests, LIGA PMMA micromirrors on the silicon surface maintain still good adhesion. The reflectance of thin gold-coated PMMA mirror of 2.52μm thickness is measured 91.3% at λ=1330nm, 92.1% at λ=1550nm, respectively. There is no thermal damage of the micromirror surface for 30 hours at -13dBm and λ=1550nm. I believe this polymer-based PMMA micromirror, combined with the standard micromachining technology, would be a promising alternative for the integration of MOEM optical switch application.
論文審査結果の要旨

半導体集積回路技術を発展させた「マイクロマシンニング」と呼ばれる微細加工技術で、チップ上に微細な構造体やアクチュエータと呼ばれる運動機構などを一体形成することで、小形で高速な動きをするシステムを安価に供給できる。インターネットに代表される光通信技術は大きく進歩しているが、そのシステムを構成する要素として、高性能な光スイッチが求められている。

本論文は、基板の上に犠牲層と構造体層を形成しておく、犠牲層を除去することで動く構造を形成する「表面マイクロマシンニング」と呼ばれる技術を用いて、光スイッチを製作する研究についてまとめたもので、全文7章よりなる。

第1章は序論であり、本研究の背景及び目的を述べている。

第2章では、光スイッチの設計に関わるシミュレーションを含む理論的な解析について述べており、熱的な弾性変形を用いたマイクロアクチュエータについて応力分布や変形あるいは共振特性などをシミュレーションで明らかにしている。また、両端固定板ばねの座屈動作の解析を行っている。

第3章では、表面マイクロマシンニングによる製作工程で犠牲層を除去するのに必要な、フッ化水素ガスによる酸化シリコンのドライエッティングについて述べている。液体を用いたウェットエッティングの場合には、洗浄後の乾燥時に液体の表面張力で構造体が下地に張り付く「ステイション」とよばれる現象のために、不良を生じ易い。このドライエッティングの研究は有用な成果である。

第4章では、本光スイッチで重要な光反射面の製作技術に研究した結果についてのべている。反応性イオンエッティングを用いてシリコン基板を垂直に加工した側面を光反射面とするため、その面を平滑にして、金属膜を形成する方法を研究した。これによって光通信の要求を満たす光反射面を形成することに成功している。

第5章では、以上の研究成果をもとに光スイッチを開発した内容について述べている。このスイッチに通電加熱することで、熟膨張を生じさせ、座屈構造を用いた安定状態を切り替える形で動作するもので、通電を続けて無くても常態を保つことができる。設計どおりに動作し、光通信に利用できることを確認したもので、この成果は高く評価できる。

第6章は結論である。

以上要するに本論文は、ドライフリングによる表面マイクロマシンニング技術を用いて、光スイッチを製作する研究を行い、光通信のための要素開発に貢献したものであり、機械電子工学および微光電気機械システム工学の発展に寄与するところが少なくなないと考えられる。

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。