SINGLE-MASK, HIGH ASPECT RATIO, 3-D MICROMACHINING OF BULK TITANIUM

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ABSTRACT
This paper reports the development of a simple method for 3-D microfabrication of complex, high aspect ratio structures with arbitrary surface height profiles in bulk titanium. The method relies on the exploitation of Reactive Ion Etching Lag (RIE Lag) to simultaneously define all features using a single lithographic masking step. Modulation of the mask pattern openings used to define the features results in etch depth variation across the pattern, which is then translated into surface height variation through removal of the superstructures above the etched floor. The utility of this approach is demonstrated in the fabrication of a sloping electrode structure intended for application in bulk micromachined titanium micromirror devices.

1. INTRODUCTION
The recent development of highly anisotropic titanium bulk micromachining processes has provided the opportunity for extension of titanium microfabrication capability well into the third dimension [1]. While this capability has enabled fabrication of complex, prismatic, 3-D projections of the planar mask pattern used to define them. For some applications, however, truly 3-D structures are desired, especially those that possess arbitrary surface height profiles, i.e. surfaces with multiple height levels and/or non-planar profiles. One example of this is the hybrid micromirror device pictured in Fig. 1, in which a wedge-shaped sloping electrode geometry is used to reduce drive voltage without sacrificing switching speed or angular displacement range of the mirror [2]. The device is composed of large bulk titanium mirrors suspended by high aspect ratio titanium springs over single crystal silicon sloping electrodes. Preliminary results have shown that the hybrid devices exhibit acceptable performance, however, the use of silicon for the electrodes may have implications on durability and reliability. The low fracture toughness of silicon may limit shock resistance and residual stresses induced by the thermal expansion mismatch between silicon and titanium could cause distortion or delamination of the mirror structures. Mitigation of issues such as these thus provides the motivation for development of 3-D micromachining processes that enable fabrication of complimentary titanium sloping electrodes.

2. SINGLE-MASK, 3-D MICROFABRICATION
Realization of 3-D micromechanical structures commonly requires multiple lithographic masking and etching steps, often on surfaces with large topographical variation. This can add significant process complexity, therefore illustrating the need for development of simpler processes. Among the multitude of 3-D micromachining techniques reported in the literature, two general types stand out for their reliance on high-throughput, batch-scale processes that are: a) compatible with conventional semiconductor process technologies; and b) require only a single masking step.

The first of these techniques involves the use of gray-scale lithography to define arbitrary surface height profiles in photoresist that are then transferred into the substrate using anisotropic RIE. This technique has been used to fabricate a variety structures [3,4], however, dependence upon stringent control of both the initial photolithography and the selectivity of the subsequent etching significantly reduces process latitude, which can have implications on reproducibility and yield.

The second batch-scale, single-mask technique for 3-D micromachining relies on the exploitation of RIE Lag, an otherwise undesirable etching phenomena in which transport limitation causes scaling of etch depth with mask opening size [5]. In this technique, structures are defined by mask patterns composed of assemblages of etch vias of varying size, shape, and pitch. Deliberate modulation of the size and/or pitch of these vias results in etch depth variation across the pattern, which is then translated into surface height variation through removal of the superstructure above the etched floors. The technique is relatively tolerant of
subtle lithographic process variations, and does not depend strongly on selectivity, therefore making it more robust than gray-scale lithography.

Similar RIE Lag-based 3-D micromachining techniques have been previously reported in single crystal silicon for the fabrication of microlenses [6] and non-planar electrodes for acoustic ejectors [7]. However, the current work represents the first known application towards bulk titanium. In this paper, the RIE Lag-based process is described and its utility for simplified 3-D micromachining is demonstrated through the fabrication of titanium sloping electrodes.

3. Fabrication

The process begins with the deposition of a TiO₂ etch mask on a polished bulk titanium substrate using DC reactive sputtering of a titanium target in an oxygen environment. The mask is then patterned using standard lithographic techniques. All components of the device are patterned in this step, therefore eliminating the need for additional lithographic steps later in the process. Figure 2 shows a portion of the lithographic mask pattern used. The pattern is primarily composed of square etch vias, ranging in size from 1.5 µm to 4.5 µm, with line widths fixed at 1 µm throughout to facilitate superstructure removal at a later stage in the process.

The lithographic pattern is transferred to the mask oxide (Fig. 3a) using a CHF₃-based dry etch, and then anisotropically dry etched into the underlying titanium substrate (Fig 3b) using the recently developed Titanium ICP Deep Etch (TIDE) Process [8]. The TIDE Process enables highly anisotropic etching of bulk titanium using a high density Cl/Ar-based plasma and provides etch rates of up to 2 µm/min with good mask selectivity (~45:1 Ti:TiO₂). After deep etching, the superstructure above the etched floor is removed using hydrofluoric acid (HF) wet etching (Fig 3c), thus yielding a surface whose topography is defined by the previous etch depth variation.

![Figure 2. Portion of mask pattern used for definition of the titanium sloping electrodes.](image)

![Figure 3. Titanium sloping electrode process flow: a) TiO₂ mask patterning via PR mask and CHF₃-based dry etch; b) anisotropic Cl-based titanium dry etch; and c) superstructure removal via isotropic HF-based wet etch.](image)

![Figure 4. Bulk titanium sloping electrode structure.](image)

![Figure 5. Optical profilometry scan of titanium sloping electrode structure pictured in Fig. 4.](image)
4. DISCUSSION

Despite the demonstrated versatility of this process for simplified fabrication of complex 3D structures in bulk titanium, minimization of surface roughness could prove problematic for some applications. As illustrated in Fig. 6, the lateral convergence of etch fronts from adjacent trenches during the superstructure removal results in the formation of sharp, peak-like protrusions beneath the original superstructure sidewalls. The magnitude of this roughness could be reduced with further HF etching. However, the isotropic nature of such smoothing would also reduce the cross-section of fine features, such as the thin interconnect lines, which could comprise their structural integrity. As a result, the degree of surface roughness reduction that could be achieved would be constrained by the degree of cross-sectional thinning that could be tolerated. Although such roughness was not a concern for the previous silicon-based sloping electrodes (R_a~100 nm) it can cause difficulties for the current titanium sloping electrodes, as will be discussed below.

Upon completion of the superstructure removal, physical definition of all structures is complete. For the case of the sloping electrode structure, however, further steps are needed to create the electrically active, but isolated surfaces required for electrostatic actuation of the micromirror device. In the prior silicon-based electrodes thermal oxidation was used to electrically isolate the surfaces of the device from the underlying substrate. Blanket gold deposition via e-beam evaporation was then performed to create electrically active surfaces on top of the structures. The tall, vertical sidewalls of the structures, coupled with the poor step-coverage of the e-beam deposition, prevented continuity of metallization between the upper surfaces of the structures and the substrate below. This resulted in self-definition of electrically isolated structures on the upper surfaces of the structures, which therefore eliminated the need for additional patterning on surfaces with large surface height variation.

A similar isolation scheme could be applied towards the current titanium-based sloping electrodes. However, in this case, a deposited insulator must be substituted for the thermal oxide insulation layer used in the silicon electrodes, due to the semiconducting nature of TiO_2. Figure 7 shows the initial results of such a process in which 1 µm of SiO_2 has been deposited on the titanium electrode structure by CCP-based PECVD at 250 °C. It is immediately apparent that the oxide deposition is rather non-uniform, as evidenced by nodular deposition on both the sidewalls and the sharp peak-like protrusions on the upper surfaces of the sloping electrode. Such non-uniformity was not an issue in the previous silicon-based electrodes because growth of thermal oxide enabled preservation of the original surface contours.

The presence of these nodular deposits on the sharp peaks of the bonding frame surfaces could detrimentally affect the uniformity of the mirror/electrode gap in the final micromirror devices by locally impeding bonding between the mirror layer and electrode substrate. The presence of such nodules on the sloping electrode surfaces could also cause undesired contact between the electrode and the mirror, therefore enabling shorting to occur, particularly in areas close to the apex of the sloping electrodes where the mirror/electrode gap can be as small as 1 µm. Improvement of the conformality of the oxide deposition, through process optimization and/or migration to a more capable ICP-based deposition system, would likely reduce the size and extent of the nodules. However, it is highly unlikely that nodular deposition on the sharp peak-like protrusions could be eliminated altogether. Nodule formation could also be mitigated by smoothing of the sharp peaks through additional wet etching before oxide deposition. However, as discussed earlier, such smoothing would likely be at the expense of the thin interconnect lines.

The reliability of the deposition-based isolation scheme described above could also be detrimentally affected by the large thermal expansion mismatch between the deposited oxide and the underlying titanium. This mismatch would result in the generation of considerable residual stress within the oxide, which could cause cracking or delamination of the layer. Substitution of Si_3N_4 for SiO_2 in this isolation scheme would reduce residual stress, due to the smaller thermal expansion mismatch differential. However, even at reduced levels such stresses might still cause distortion or delamination of the mirror layer, especially with repeated temperature cycling, thus suggesting the need for consideration of alternate isolation schemes.
5. CONCLUSION

In summary, a simple 3D micromachining process for bulk titanium has been demonstrated. The process, based on exploitation of an RIE Lag-based process originally developed for silicon, enables fabrication of complex structures with arbitrary surface profiles using only a single lithographic patterning step. Application of the process towards the fabrication of titanium sloping electrodes for an all-titanium micromirror device, however, reveals certain limitations that will need to be addressed before such devices can be realized. Development of Titanium on Insulator substrate technology is identified as one means of circumventing these limitations.

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6. REFERENCES