DEVELOPMENT OF BULK-TITANIUM-BASED MEMS RF SWITCH FOR HARSH ENVIRONMENT APPLICATIONS

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ABSTRACT

This paper presents an investigation into the viability of a new route for the fabrication of titanium-based MEMS RF switches for harsh environment applications. Titanium’s intrinsic toughness and corrosion resistance suggest that it would be highly suitable for such applications and recently developed titanium micromachining technologies now make exploration of this potential possible. Two design generations of electrostatically-actuated Bulk-Titanium MEMS (BT-MEMS) switches were fabricated and tested. First generation devices demonstrated that actuation at moderate voltages could be achieved (~60V), however stiction upon contact was common. This stiction was mitigated in the second generation devices through design modification and development of a new Titanium on Insulator (TOI) based process. These devices displayed stiction-free actuation and relatively low contact resistance (~1Ω). These preliminary results therefore demonstrate the potential of this process technology for fabrication of titanium-based RF switches for harsh environment applications.

Keywords: Bulk Titanium, BT-MEMS RF switch, high-aspect-ratio etching, multilayer lamination, and Titanium on Insulator (TOI).

INTRODUCTION

Recently, MEMS-based RF-switches have begun receiving increasing attention because of their potential for reduced power consumption, excellent linearity, low insertion-loss, and high isolation [1,2]. Considerable efforts have been directed towards development of such switches, predominantly through surface micromachining of a wide variety of micromechanical materials systems, including silicon [3], polysilicon [4], silicon dioxide, silicon nitride, and various metals [5-7]. However, deposition-based processes such as these are often prone to limitations that can complicate fabrication and detrimentally affect device performance. Some of these include: limited layer thickness capability, which limits stiffness and mechanical restoring force; deposition-based stress gradients that can cause undesirable buckling of released structures; and release-induced stiction caused by insufficient control of the sacrificial layer removal process. Moreover, need also exists for development of switches capable of operation under harsh environment conditions where resistance to high g-forces, corrosive attack, large thermal excursions, etc. is required. Such environments limit the use of many more conventional micromechanical materials. The current work discusses efforts underway to address these issues through the development of a Bulk-Titanium MEMS (BT-MEMS) RF switch realized using high-aspect-ratio bulk titanium micromachining and multilayer lamination techniques.

Titanium offers many advantageous properties relative to other micromechanical materials, including high fracture toughness and excellent corrosion resistance. Consequently, titanium is an attractive candidate for harsh environment MEMS RF switches. Using recently developed micromachining techniques based on Cl₂/Ar dry etching [8,9], high-aspect-ratio structures with micrometer-scale features and vertical sidewalls can be achieved in both thick substrates and thinner freestanding foil substrates. Thin foils can also be through-etched and bonded to other substrates to enable the realization of complex multilayered devices. These foil substrates can be
obtained in thicknesses ranging from 10 µm to many hundreds of micrometers with minimal residual stress. This therefore allows greater design flexibility compared to deposition-based techniques where layer thickness is limited and residual stresses can cause undesirable deformation of the device structures [10]. Furthermore, reliance upon multilayer lamination of through-etched foils eliminates the need for use of sacrificial layers, thus reducing process complexity as well.

FABRICATION

Figure 1 shows a schematic rendering of the BT-MEMS RF switch device. The device is composed of a simple cantilever switch element suspended above a substrate patterned with electrodes for capacitive actuation and contacts for RF signal transmission. Both first and second generation devices share the same general design, but differ in the processes used for fabrication of the lower electrode substrate.

The fabrication process for the first generation device, illustrated in Fig. 2, starts with TiO$_2$-masked multi-level deep etching of a 400 µm thick Ti substrate using Inductively Coupled Plasma (ICP) etching in an Ar/Cl$_2$ ambient. The substrate is then coated with PECVD SiO$_2$ followed by blanket e-beam deposition of Au to form the Electrodes and Contact Pads. The switch element is fabricated separately by through-etching a 25 µm thick Ti-foil, which is then attached to the thick Ti substrate using aligned Au thermocompression bonding.

Note that in this first generation design both the Electrodes and Contact Pads are at the same height, and the gap between them and the Switch Element above is determined by the etch depth into the bulk substrate, rather than through the use of a sacrificial layer. Also note that electrical isolation of the electrodes and signal lines from the substrate and one another is achieved without the need for lithographic patterning on the deep etched structures. This is made possible by the tall vertical sidewalls of the etched structures, coupled with the poor conformality of the e-beam deposition, which prevents continuity of deposition [11].

Figure 3 shows a completed first generation device. The picture is taken on an interferometric microscope (Wyko NT1100 Optical Profiling System) which shows that a 600 µm long flat beam is achieved and it’s parallel to the bottom floor. Displacement at the electrode and contact area verifies that the gap (1.5µm) is well controlled by etching at very low etch rate. Impurity-induced micromasking at the grain boundaries is observed on the deepest etched regions, which indicates that the roughness at the contact areas is increased by the etching process. As will be discussed later, such roughness proved detrimental to the device performance, thus necessitating development of a second device generation.

To avoid micromasking on the contact surfaces a Titanium-On-Insulator (TOI) wafer concept was developed for the second generation BT-MEMS RF switch. Figure 4 illustrates the new fabrication procedure, in which an additive, surface micromachining-based approach is used to build up the desired Electrode and Contact Pad structures. The process begins with deposition of a 3 µm SiO$_2$ layer on a thick Ti substrate followed by sputter deposition of Ti. The sputtered Ti layer is then patterned using Ar/Cl$_2$—based dry etching to form the bonding pads and contact areas. Sputtered Au is deposited thereafter to form electrodes and contact pads using liftoff-based processes. The upper substrate is fabricated and bonded to the lower substrate using the same procedures previously described for the first generation devices. It should be noted that use of a deposition-based process for these TOI substrate structures does not render them susceptible to the previously mentioned shortcomings of surface micromachining. The structures defined in the sputtered Ti film remain fixed to the 400 micron thick substrate and do not require large thicknesses.

Fig. 1: Schematic of the first generation BT-MEMS RF switch.

Fig. 2: Process flow for the first generation device.

Fig. 3: Interferometric microscope picture (by Wyko NT1100) of the first generation device.
Unlike the previous devices, the Electrodes in the second generation devices are recessed relative to the Contact Pads to reduce the likelihood of collapse of the actuator due to pull-in. The design of the cantilever switch elements is also modified to increase stiffness and electrode area is increased to ensure moderate actuation voltages. Figure 5 shows an SEM micrograph of the second generation device. As can be seen in Fig. 6, the TOI process enables fabrication of contact surfaces which are devoid of the micromasking-induced roughness and grain boundaries.

RESULTS AND DISCUSSION

Figure 7 demonstrates that successful closure of the first generation switch occurred at ~60V. However, contact resistance at this voltage was undesirably high (>2Ω) and was not reduced with increased voltage. Furthermore, application of 80V or greater resulted in occasional stiction to the contact pads which would persist for several minutes. Permanent stiction would occur when voltage exceeded 150V, due to electrostatic pull-in of the upper electrode. The resonant frequency of the devices, measured using Laser Doppler Vibrometry, was 23 kHz.

The large contact resistance in these first generation devices was most likely caused by the roughness of the contact pads, which acted to reduce effective contact area. It is also possible that this roughness exacerbated stiction, especially when coupled with the inadequate restoring force of the cantilever switch elements and low hardness of Au.

Figure 8 shows the contact resistance in the second generation devices as a function of actuation voltage during application of a 100V square wave function. Closure of the switch in this particular device was possible at 40V, but higher voltages were necessary to give stable contact resistance (~1Ω). The measured resonant frequency of the devices was 16 kHz, which was lower than that of the first generation devices, primarily due to the increased mass of the larger electrode plate.

Fig. 7: Displacement at electrode and contact areas of the first generation device. The upper plot shows that contact occurs at ~60 V. The electrode and the cantilever tip displaced the same amount (1.6µm) after pull-in, which verified that the beam was parallel to the bottom floor.

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contact resistance at 100Hz sampling frequency under 10 Hz square wave (blue) input voltage on the driving electrodes.

The second generation device can operate at above 10 kHz. However, contact resistance testing was performed at 10 Hz in order for the Precision Semiconductor Parameter Analyzer (HP 4156A) to record the instant measurement value. The broken line above the square wave function shows 50 contact resistance sampling points among the first 100,000 actuation cycles.

As can be seen, the modified design and fabrication of the second generation devices enabled reduction of contact resistance and elimination of stiction problem over the limited duration of testing performed thus far (~100,000 cycles). The reduction of contact roughness by the use of the TOI structure decreased contact resistance by increasing effective contact area, which was likely asperity-limited in the first generation devices. The increased restoring force of the stiffer springs, coupled with the reduction of contact roughness, reduced the likelihood of stiction. Additional stiction mitigation also arose from the use of sputtering for deposition of the Au contacts, rather than evaporation, as was used in the first generation devices. The finer grain size produced by sputtering increases hardness and therefore reduces material transfer during contact. Further improvement of device performance through additional optimization of the mechanical design is possible, but beyond the scope of this preliminary study. The current results demonstrate, however, the potential advantages of this new fabrication technology relative to surface micromachining, which include: the reduction of layer thickness constraint; elimination of need for control of film stress; and elimination of the need for sacrificial layers. Consequently, the simplification of fabrication, coupled with the intrinsic harsh environment resistance provided by titanium, suggests that this process technology shows considerable potential. Future work will focus on further characterization of the current devices with regards to lifetime, and exploration of methods to mitigate stiction through the use of new contact materials.

CONCLUSION
Bulk-Titanium MEMS RF switches were successfully fabricated and tested using recently developed high-aspect-ratio micromachining and multilayer lamination techniques. The devices show promising performance and the fabrication processes developed enable reduction of process complexity relative to more conventional routes. This therefore demonstrates the potential for realization of robust switches that can operate in harsh environments that are otherwise difficult, if not impossible with prevailing process technologies.

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