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Failure of Au RF-MEMS switches subjected to dynamic loading

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ABSTRACT

The dynamic failure of Au RF-MEMS was investigated over a wide range of loading rates by three different experimental setups: a drop weight tower, which induced a maximum peak acceleration of 600*g* (*g*: acceleration of gravity), a Hopkinson pressure bar with a maximum peak acceleration of 300,000*g*, and a pulsed laser loading technique with a maximum peak acceleration of $1.8 \times 10^8 g$. In the drop weight tower the total load pulse duration was in the milliseconds range – much longer than the 28 μs resonant period of the devices – and no failure of any kind occurred in the RF-MEMS devices or their substrate. At 90,000*g* (generated in the Hopkinson bar) no damage in either the substrate or the devices was observed. However, at 200,000*g*, which corresponds to a loading duration of a few microseconds, *i.e.*, comparable to the device resonant period, 10% of the switches failed although postmortem imaging showed no damage to the substrate. Damage increased after this acceleration and at 300,000*g* 20% of the switches failed, but, in addition, significant failure in the quartz substrate was recorded. Lastly, the pulsed laser loading technique, which has a loading pulse duration of a few tens of nanoseconds, was applied to accelerate the Au switches to $1.8 \times 10^8 g$, and the probability of failure at this loading ranged from 50% to 80%. At even larger accelerations, $10^9 g$, the probability of failure was 100%. The results of this study establish the severity of dynamic failure in MEMS, despite their small mass, and its dependence on the level of acceleration which spanned about 7 orders of magnitude.

1. Introduction

Microelectromechanical Systems (MEMS) have become increasingly prevalent in both commercial and military applications that entail adverse pressures, stresses and accelerations. There is a plethora of examples including high acceleration inertial measurement units, angular rate sensors for hypervelocity systems, phased arrays for tactical seekers, embedded sensors for monitoring and control of weapon systems, trigger devices, *etc*. Many of these devices are to be integrated in weapon systems that during storage or operation undergo extreme loading rates (*e.g.*, tank munitions or delayed charge sensors in "bunker busters") which the devices must survive both structurally and intrinsically. Tank munitions, for instance, can reach accelerations in the order of 100,000*g* (*g*: acceleration of gravity), with instantaneous accelerations possibly being higher in some cases [1,2].

Because of the broad range of possible loading types and rates, it is important to develop methods for assessing device dynamic failure in a reliable manner. Several researchers have used various methodologies to investigate dynamic failure in MEMS. Srikar and Senturia [3] developed a model for predicting failure of MEMS devices subjected to shock loads. They pointed out that the response of the device is dictated by the relationship between acoustic transit time (*i.e.*, wave speeds), applied loading duration and vibration timescales that are particular to devices, and can be classified into three regimes based on the wave propagation times, resonant periods, T, and loading duration, τ: (a) quasi-static, corresponding to loading duration greater than the resonant period ($\tau > 2.5T$); (b) resonant, when the loading duration is of the order of the resonant period of the device ($0.25T < \tau < 2.5T$); and (c) impulse, when the loading duration is much shorter than the resonant period ($\tau < 0.25T$), *e.g.*, of the order of wave propagation times. Srikar and Senturia [3] tested arrays of one thousand twenty-four 1-cm long polycrystalline silicon beams that were 2 μm thick and 10 μm wide. Loading pulses were generated by a shock table, with amplitudes of 3000*g* and durations between 300 and 400 μs. Post-experimental optical inspection did not reveal any damage in either the silicon substrate or the MEMS beams. Based on this, Srikar and Senturia [3] concluded that dynamic failure is not likely to occur in MEMS in the range of accelerations they investigated.

Nonetheless, this type of loading can still interact with the operation of MEMS devices and cause intrinsic operational, rather than mechanical, failure as has been predicted and observed in the works of [4–7]. In [5,6] Younis et al. conducted computational studies

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to investigate failure modes of MEMS subjected to low levels of dynamic loading. In [7] they also performed an experimental study, coupled with the previously developed model, to design capacitive switches capable of responding at dynamic loading conditions of 10 s of *g*s.

The reliability of MEMS microengines under higher frequency vibration loading was experimentally evaluated in [8]. The duration of their tests was 3 min, with loading frequencies from 20 to 2000 Hz, and peak acceleration near 120*g*. Failure was defined when the drive gear could not make a complete revolution at the inspection frequency. Although many of the microengines did not pass the failure criterion, it was determined that the majority of the failures were not a result of the vibration testing. Therefore, in Tanner et al. [8] a total of only two of the nineteen functional microengines were determined to have failed as a result of vibrational loading.

Brown et al. [2] conducted environmental and dynamic loading experiments on MEMS resonators. A drop test provided peak accelerations of up to 35,000*g*, while accelerations up to 100,000*g* were achieved by launching the sensor in an aluminum carrier body from an air gun. The majority of the MEMS tested survived the loading structurally. However, the few times when failure did occur it was due to stiction, detached beams, or jump shifting, *i.e.*, failure modes that were not associated with material fracture or interfacial delamination.

Therefore, it is reasonable to assume, as suggested by Srikar and Senturia [3], that at the aforementioned acceleration rates, MEMS are not susceptible to dynamic loading induced mechanical failure because of their small size and mass—although failure of device functionality is possible [5–7]. However, according to Duesterhaus et al. [9], higher acceleration levels, or lower accelerations but for long duration, will cause MEMS devices to fail mechanically, despite their small inertial forces. In their experiments, dynamic loading was applied on MEMS devices that were fabricated by the SUMMIT^{TM} process and included cantilever beams (ranging in length from 200 to 1000 μm, and square anchor length from 4 to 12 μm), microengines, resonators, and thermal actuators. The specimens were loaded in tension or compression by a Hopkinson pressure bar. Failure was defined for both beams and actuators as the sign of any physical breakage and, additionally for the actuators, as functional failure. The results of Duesterhaus et al. [9] indicated that MEMS are less likely to survive displacements away from the substrate that result from tensile loading. Up to 50% of the components in each category failed at a tension shock of 50,000*g*, whereas the majority of the components survived a compression shock of 250,000*g*. Additional field testing of specimens was conducted at peak accelerations of 3000*g* for 5 ms. These lower, but of longer duration, acceleration profiles also resulted in MEMS failure.

Motivated by the work of Duesterhaus et al. [9], Kimberley et al. [10,11], employed a pulsed laser loading setup, similar to that used in laser spallation experiments, to produce dynamic loading of MEMS at extreme acceleration levels of up to 10^9*g*. In Kimberley et al. [10] polysilicon MEMS devices manufactured at the Sandia National Laboratories were investigated, while in Kimberley et al. [11] MEMS manufactured at the Army Research Laboratory were of interest. In both cases, significant device damage and failure was established in the form of both material failure (*i.e.*, fracture) and delamination between layers. Details of the failure mechanisms were probed by companion finite element simulations. It was found that the local material and geometry characteristics (*i.e.*, stress raisers) significantly promote failure.

From the works quoted above, it is clear that dynamic failure of MEMS is dependent on the loading rate and duration, and on the material type and geometry. In light of this, the scope of the work presented herein is to (a) develop methods of experimentally analyzing the dynamic response of MEMS devices over a *far wider range* of strain rates and accelerations than previously done, and (b) determine the maximum threshold of dynamic loading where no damage can be detected, and the nature of damage once it occurs. In the present investigation all methods were applied to the *same type of devices*, thus, avoiding to derive conclusions from the application of different methods and device/specimen geometries.

2. Experimental methods

Early studies on polysilicon MEMS loaded dynamically have shown a dependence of failure modes on rate and device geometry [9,10]. However, the large strength of polysilicon compared to metals [12,13] does not allow direct extrapolation from one material system to the other. In order to investigate how ductile material selection influences dynamic failure, Au-based MEMS structures were used in the present work. Fig. 1(a) shows a scanning electron microscope (SEM) image of an array of Au RF switches on quartz substrate [14]. On each chip, several arrays were placed in rows, with each row partitioned by a score line in the substrate. All of the gold RF switches were designed to be identical, each with a membrane layer of 0.5 μm of Au on top of approximately 10 nm of Cr. Fig. 1(b) details the cross-sectional dimensions of the 300 μm long RF switches. The dimples seen in Fig. 1(b) prevent the entire adhesion of the devices onto their substrate. The initial state of the devices, along with the inherent material variability, may lead to a statistical nature of device failure under loading.

Dynamic loading of MEMS devices could be in either the resonant or the impulsive categories in which the loading timescale is comparable to either the MEMS resonant or wave transit times, respectively [3]. Although the transition between these two regimes is not clearly defined, it is evident that different loading devices are necessary to span the associated, orders of magnitude, range in loading acceleration. To date, studies on dynamic failure of MEMS have limited their focus to a single loading rate, or a small range of similar loading rates [9–11]. In the present work, we employed three different loading devices to produce dynamic loading ranging from resonant to impulsive on the same MEMS chip designs,

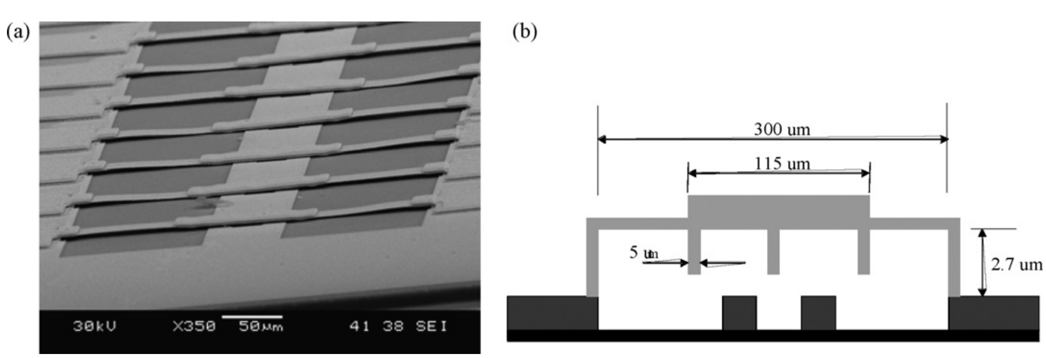

Fig. 1. (a) SEM micrograph of an array of undamaged gold RF switches and (b) cross-sectional view of gold RF switch.