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Mechanics of energy transfer and failure of ductile microscale beams subjected to dynamic loading

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ABSTRACT

The mechanical response of microelectromechanical systems (MEMS) under impulse loading conditions has not been thoroughly studied to date, partially because of the lack of means to provide such extreme loading rates to miniature devices. However, the increasing use of MEMS-based sensors and actuators in adverse environments, which include extreme strain rate loading, has motivated the investigation of the response of MEMS components under these conditions. In this work, basic and mostly commonly employed Au MEMS components were subjected to impulse loads of 40 ns in duration, which were generated by a high power pulsed laser in order to achieve acceleration levels on the order of 10^9g. This allowed for the microdevice mechanical/structural response to be investigated at time scales that were of the order of wave transit times in the substrate and the devices. Basic microscale structures, such as cantilevers and fixed-fixed beams of uniform cross-section, were employed to facilitate comparisons with companion finite element simulations in order to gain insight into the mechanisms responsible for impulsive deformation at the microscale. The simulations investigated the effect of loading rate, boundary conditions, beam length, material constitutive response, and damping on the final deformed shapes of the beams. It was found that contact and momentum transfer mechanisms were responsible for the large permanent beam deflections which were measured postmortem. Additionally, the effects of both damping and material property rate dependence were found to be dominant in determining the final deformed shape of the beams. In fact, our observations suggest that the contributions of material rate dependence and damping are not simply additive, but rather involve a coupling between them that affects the final structure response.

1. Introduction

Microelectromechanical systems (MEMS) are small scale devices with structural lengths of the order of micrometers that are designed to achieve a wide array of capabilities by combining electrical and mechanical functions. MEMS devices are typically manufactured by using techniques adopted directly from the integrated circuitry industry. Several optimized technologies, such as the Sandia ultra-planar multi-level MEMS technology—SUMMiT (Sniegowski, 1996) and the multi-user MEMS process—MUMPS (Markus et al., 1995), have been developed with the explicit purpose of designing and

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manufacturing microdevices with increased complexity. Applications of these devices cover a wide range of areas, such as mechanical sensing (accelerometers for automotive airbag deployment, pressure sensors), mechanical actuation (microengines), and power transmission (gear trains).

While the development of microscale technologies and the associated devices is still fairly new, substantial research has been conducted concerning the mechanical response of the materials used in common MEMS devices. However, the bulk of the existing work has been concerned with the quasi-static constitutive and failure responses of the materials, see for example a review by Chasiotis and Knauss (2003a) and papers by this group (Chasiotis and Knauss, 2002, 2003b, c; Cho and Chasiotis, 2007), and to a lesser extent with fatigue response, see for example Muhlstein et al. (2001), Kahn et al. (2002), Bagdahn and Sharpe (2003). A few studies have investigated MEMS failure due to dynamic or shock loading, but most of them have concentrated on polysilicon MEMS (Brown et al., 2001; Wagner et al., 2001; Duesterhaus et al., 2004; Kimberley et al., 2008). An example is the work of Duesterhaus et al. (2004) who loaded arrays of polysilicon cantilever beams at up to 250,000*g* of compressive, tensile, and shear accelerations. The naming convention of the accelerations was defined with respect to the initial motion of the structures relative to the substrate, with “compressive” referring to structures initially moving toward the substrate, “tensile” to accelerations causing initial motion away from the substrate, and “shear” resulting in motion parallel to the substrate. Each die contained arrays of 20-μm wide cantilevers of lengths ranging from 200 to 1000 μm attached to the substrate with square anchor cuts of side lengths varying from 4 to 18 μm. It was observed that beams with smaller anchor undercuts failed in the anchor connection, while larger anchor undercuts showed failure at the root of the beam indicating flexural failure, illustrating that there may be a transition of failure modes that is dependent upon structural length for a given loading time scale.

Metal thin films have also been incorporated quite extensively in MEMS, especially in the most recent years. They are in the form of active devices, such as RF switches, varactors, *etc*., or as supporting elements, *e.g*., electrodes, for other active materials. Building on the limited prior work on polysilicon MEMS, recent experimental work by our group has focused on the dynamic failure of Au RF-MEMS (Kimberley et al., 2009). To generate loading over a large range of rates, Kimberley et al. (2009) used three different loading devices: a drop weight tower, a modified split Hopkinson bar, and a pulsed laser loading set-up (also used in the present study). Identical arrays of Au RF-MEMS switches were loaded dynamically by using each of these techniques. In the drop weight tower, with induced peak accelerations of about 3500*g* and total load pulse duration in the ms range, no failure of any kind was observed in the MEMS devices or the substrate. In the Hopkinson bar, with peak accelerations ranging from 90,000 to 300,000*g*, progressively larger numbers of RF-MEMS switches failed as the loading level increased, from 0% failure probability at 90,000*g* to 20% at 300,000*g*. This progressive increase of failure probability suggests that the statistical nature of small scale device failure observed during quasi-static loading will likely carry over into the dynamic case.

In the work of Kimberley et al., 2008 on the ultra-high rate dynamic response of polysilicon MEMS, a combination of experiments and numerical simulations, especially tailored to the experiments, showed the importance of local geometrical features in the observed failure response. From the above results it is clear that dynamic failure in MEMS does indeed occur, despite their small mass, but it is likely dependent, among other things, on the level of acceleration, the total time duration of loading, the device geometry and the material. However, in light of the very limited available information, especially into the details of which quantities/properties affect dynamic MEMS failure and how, one needs to move beyond a simple postmortem observation of failure of MEMS and rather concentrate on understanding the underlying mechanisms that lead to the observed failure modes. Unfortunately in the work of Kimberley et al., 2009 on Au RF-MEMS switches, the device complexity did not allow for immediate correlation of the observed damage with a particular mechanism of damage initiation and propagation. Therefore, in the present work we concentrate on understanding the mechanisms responsible for dynamic failure of Au MEMS devices of simple geometrical shapes of either a cantilever beam or a fixed–fixed beam. A series of experiments that generate impulsive load on the MEMS devices is described in Sections 2 and 3. Companion numerical analyses that simulate the experiments as faithfully as possible are discussed in Section 4, and several conclusions are drawn in Section 5.

2. Experimental methodology

2.1. Material and test device fabrication

Test dies were designed at the University of Illinois, and were subsequently manufactured, by the Sensors and Electron Devices Directorate of the Army Research Laboratory (ARL) so that a large number of identical Au structures of simple geometries and boundary conditions could be tested in each experiment. Each die was populated with fixed-fixed and fixed-free (*i.e*., cantilever) beams with lengths ranging from 20 to 200 μm in increments of 20 μm. All beams were 20 μm wide, but the shape and size of the attachment anchor was either a 105 μm circle or square (large anchor) or a 65 μm circle or square (small anchor). The Au comprising these beams was deposited on top of a 2 μm-thick sacrificial photoresist layer that allowed for the beams to be released from their substrate using the same process described by Polcawich et al. (2007) for ARL’s piezoelectric RF-MEMS switch. In order to connect the Au thin film structures to the Si substrate, a 20/730 nm-thick layer of Ti/Au was first deposited via electron beam evaporation and was patterned to form a square or a circular anchor. The 2000 nm-thick Top-Au layer (designated as “Top-Au” because it is used as the topmost layer in the fabrication