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Inelastic deformation of bilayer microcantilevers with nanoscale coating

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ABSTRACT

The application and commercialization of microelectromechanical system (MEMS) devices suffer from reliability problems due to the structural inelastic deformation during device operation. Nanocoatings have been demonstrated to be promising solutions for suppressing creep and stress relaxation in bilayer MEMS devices. However, the micro/nano-mechanics within and/or between microcantilevers and coatings are not fully understood, especially when temperature, time, and geometric and material nonlinearities play significant roles in the thermomechanical responses. In this study, the thermomechanical behavior of alumina-coated/uncoated Au/SiN$_x$ bilayer microcantilevers was characterized by using thermal cycling and isothermal holding tests. Finite element analysis with power-law creep was used to simulate the mechanical behavior of microcantilevers during isothermal holding. To better understand the stress evolution and the mechanism of inelastic deformation, scanning electron microscopy and atomic force microscopy was employed to explore the grain growth and grain boundary grooving after isothermal holding at various temperatures of 100 °C, 150 °C and 200 °C. The methods and results presented in this paper are useful for the fundamental understanding of many similar bilayer microcantilever-based MEMS devices.

1. Introduction

Bending of bilayer microcantilevers is widely employed in MEMS for a variety of sensor and actuator applications. The bilayer microcantilever sensors including infrared (IR) detectors [1], thermal detectors [2] and calorimetric high frequency detectors [3] rely on the thermal expansion mismatch induced deformation upon energy absorption. Subsequently, the deformation can be readily determined by means of piezoresistive, optical or capacitive methods [4–6]. On the other hand, the bending of bilayer microcantilever-based actuators can be controlled by applying a temperature change. Such actuators have been commonly used in DC electrical relays and contacts [7], radio frequency (RF) switches [8], and tunable split ring resonators (SRRs) [9]. In order to meet sensitivity and movement requirements, as well as maintaining MEMS and IC process compatibility, the bilayer microcantilever-based sensors and actuators must: (1) have a large thermal expansion mismatch between two layers; (2) be able to operate in wide temperature range; and (3) have good MEMS and IC process compatibility, so that bilayer microcantilever-based sensors and actuators have the potential of commercialization. To satisfy these requirements, one layer is typically made of metal (Au, Ni, Al. . ., etc.) and the other layer is made of ceramic (SiN$_x$, SiO$_x$, poly Si. . ., etc.) which has a much lower thermal expansion coefficient than metal [10].

From the design viewpoint, the ideal bilayer microcantilevers will deform proportionally to temperature change and do not exhibit inelastic deformation over the operation period. However, the metal layers are typically not stable after deposition [11–13]. When subjected to thermal loading, the microstructural evolution in metal layers can be triggered, such as extinction of excess vacancies, subgrain coalescence and grooving [14–18]. The microstructural evolution results in inelastic strain behavior in metal layers and thus highly inelastic deformation in bilayer microcantilevers. Neglecting the inelastic deformation can result in misinterpretations of the measurement data from bilayer microcantilever-based sensors and can compromise control precision of actuators. Hence, it is of vital importance to perform accurate thermomechanical behavioral characterization on bilayer microcantilevers and to develop an appropriate model for the description of its time-dependent inelastic deformation.

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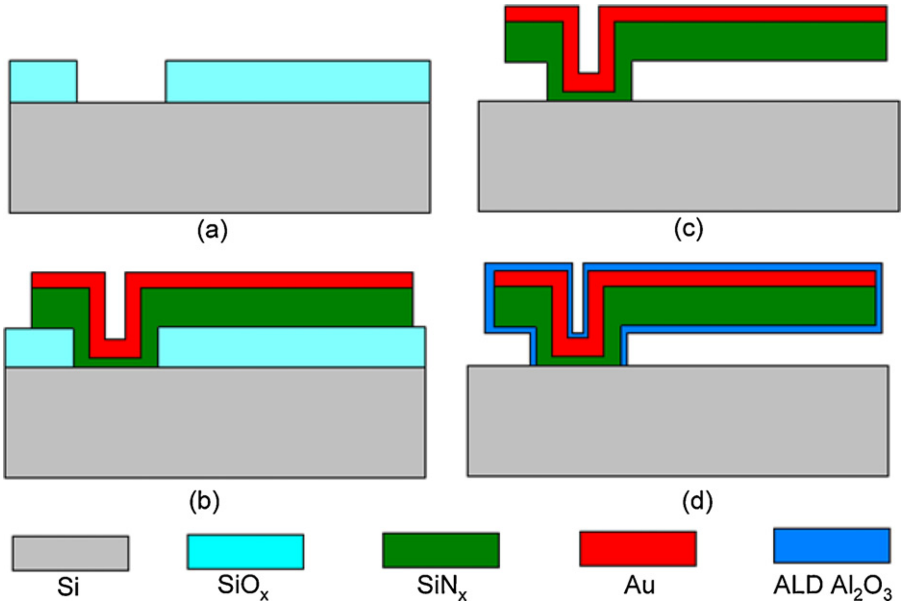

Fig. 1. Fabrication process of the Au/SiN_x bilayer microcantilever beams with nanocoating: (a) deposition of 1.5 μm thick SiO_x and etching of SiO_x by RIE with SF6, (b) deposition of a 1.15 μm thick PECVD SiN_x layer and a 0.5 μm thick e-beam evaporated Au layer, and patterning of Au and SiN_x layers using KI and RIE with SF6 and He, respectively, (c) releasing of the microcantilever beams by isotropic etching of SiO_x with BOE and then drying by supercritical CO_2 release system and (d) nanocoating of alumina by ALD.

In order to address the aforementioned needs, we studied the thermomechanical deformation of Au/SiN_x microcantilever beams with combined effects of geometric and material nonlinearities. These behaviors need to be fully understood in order to properly design, characterize and manufacture reliable MEMS structures and devices. Previous studies indicate that not only geometric nonlinearity (large deformation) can be of importance when multilayer thin film microstructures are subjected to thermal loading, but the material nonlinearity (creep, stress relaxation...) and the interaction between these two are also of equal importance in MEMS applications [11–14,17,18]. Following the same scope, we used Au/SiN_x microcantilever beams to explore the combined effect of geometric and material nonlinearity which resulted in more complex behaviors. We demonstrated that the time-dependent inelastic deformation can be suppressed by the use of nano-coatings realized by atomic layer deposition (ALD). Our study suggested that the nanoscale coating causes alternation of the stress state in the metal layer and a change in the fundamental inelastic deformation mechanisms.

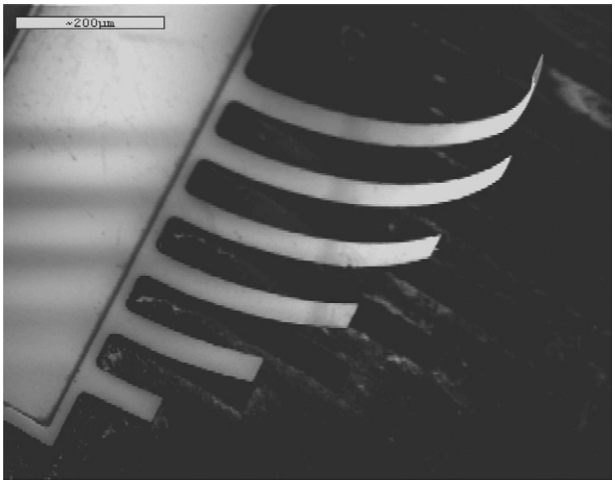

Fig. 2. SEM image of an array of Au (0.5 μm thick)/SiN_x (1.15 μm thick) microcantilever beams suspended over a silicon substrate.

In this present work, we performed a rational analysis/characterization of thermomechanical deformation on coated Au/SiN_x microcantilevers, and used finite element analysis (FEA) with power-law creep to describe the inelastic deformation of the microcantilevers over a significant period of time. Section 2 describes the fabrication of the bilayer and alumina coated microcantilever beams. Interferometric microscopy was employed to in situ measure the deformation of microcantilever beam subjected to thermal loading. Finite element analysis procedure is presented in Section 3. Section 4 describes the thermomechanical evolution and the modeling results of the deformation of microcantilever beams during thermal cycling and isothermal holding. Finally Section 5 discusses and correlates the microstructural evolution from scanning electron microscopy (SEM) and atomic force microscopy (AFM) studies to the observed thermomechanical deformation during isothermal holding on both uncoated and coated microcantilever beams.

2. Sample preparation and measurements

The bilayer and alumina coated Au/SiN_x bilayer microcantilever beams were fabricated following the process flow in Fig. 1. The testing structures consisted of 6 Au/SiN_x bilayer microcantilever beams with a 40 μm width and lengths ranging from 60 μm to 360 μm with 60 μm increments. In this study, results from the beam with 180 μm length were presented. Fig. 2 shows one of the beam arrays, where a 0.5 μm gold layer was grown on top of a 1.15 μm SiN_x layer using surface micromachining techniques with SiO_x as the sacrificial layer.

Before fabrication, Piranha solution (H_2SO_4:H_2O_2 = 3:1) and 40% hydrofluoric acid solution were used to clean the native oxides and organic residues from the ⟨1 0 0⟩ silicon wafer, respectively. The first step of the fabrication was to deposit a 1.5 μm thick SiO_x film as a sacrificial layer using plasma enhanced chemical vapor deposition (PECVD) (PECVD Multiplex, STS Inc.). The SiO_x layer was then patterned using reactive ion etching (RIE) (790, Plasma-Therm LLC.) with SF_6 gasses to create anchors for the micro-