

# Microelectromechanical Systems and Nanomaterials: Experimental and Computational Mechanics Aspects

## PREFACE

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Microelectromechanical systems (MEMS) and nanomaterials are two emerging technologies of importance in society. MEMS are currently used in a variety of applications, such as air bag deployment sensors, gyroscopes for airplane and space navigation, radio frequency (RF) devices for wireless communication, projection devices, and fabrication of gene chips. Likewise, nanomaterials possess the potential to impact major industries, e.g., the automobile, aerospace, microelectronics and medical industries. For instance, clay and carbon nanotube composites are lightweight materials expected to achieve stiffness and strength levels previously unimaginable. Similarly, nanocrystalline coatings, with their excellent magnetic, electrical and wear properties, make nanostructured materials ideal candidates for the next generation of recording media. Furthermore, their exceptional catalytic properties make them also strong contenders for fuel cell applications. An important feature of nanostructured materials, obtained by controlling chemical composition and grain size, is the ability to affect, simultaneously, more than one material property. For instance, in the case of nanocrystalline-Ni (nc-Ni), a reduction in grain size from a few micrometers to about 10 nm results in dramatic changes of about 14 properties. These changes include enhanced wear resistance by a factor of 170, hardness by a factor of 5, electrical resistivity by a factor of 3 and coercivity in single domain effects. This phenomenon creates the possibility of manufacturing *functional materials* in which several desired properties can be obtained *by design*. The understanding of *relationships between nanostructure and mechanical properties* is a common challenge to both MEMS and nanomaterials technologies.

In this special issue of *Experimental Mechanics*, 16 papers are presented, which address the testing and modeling of MEMS materials and unique and fascinating nanomaterials and biomaterials. The contributions are organized into the following areas:

- mechanical testing techniques;
- device reliability;
- on-chip testing of MEMS devices;
- stress waves in thin films;
- testing of nanomaterials;
- biomaterials function modeling.

*Mechanical Testing Techniques* are presented for the mechanical characterization of freestanding thin films using specimens with dimensions as small as a few hundred nanometers. The opening paper is a transcript of the Murray Award Lecture delivered by W. Sharpe, Jr. of John Hopkins University at the 2002 Annual Conference of the Society for Experimental Mechanics. The paper reviews the experimental techniques developed at John Hopkins for the tensile testing of MEMS materials at room and high temperatures. Other emerging techniques to probe the mechanical behavior of nano and biomaterials are also discussed. Another review article, concerning the selection of experimental techniques to measure mechanical properties, was contributed by Srikar and Spearing. These authors address the problem of common error sources in small-scale experiments and provide a rational approach to the selection of the most accurate experimental techniques. Haque and Saif present a third review article.

Here the emphasis is on specimen fabrication, small force generation and high-resolution deformation measurement for the testing of micrometer and submicrometer thin films. Two types of test, tension and bending, are discussed in detail in the context of in situ electron microscopy testing. The last paper in this subtopic, by Espinosa et al., presents the mechanical testing of a new material called ultrananocrystalline diamond (UNCD). A novel membrane deflection experimental technique is employed to characterize freestanding submicrometer thin-film elasticity and strength. The technique is the same as that used by Espinosa and collaborators in the investigation of plasticity size effects in FFC metals in the absence of strain gradients. The measured properties clearly show that UNCD is an ideal material for the development of novel MEMS and nanoelectromechanical systems (NEMS), such as atomic force microscopy (AFM) tips, nanoresonators, nanoswitches, etc.

*Device Reliability* is another subtopic emphasized in this volume. Reliability is a major concern in the microelectronics and MEMS industries. Liang, Huang, Prevost and Suo analyze the effect of integrating dissimilar materials in small devices. They show that the behavior of a channel crack advancing in an elastic film is highly dependent on the underlayer film properties. These authors also propose new experiments to measure fracture toughness and creep laws in small structures. Jones, Murphy and Begley discuss an elegant experimental technique to investigate adhesion between initially separated components. The technique is employed in both quasi-static and cyclic loading regimes. The experiments are interpreted by means of beam theory and fracture mechanics models. Soboyejo et al. report on findings concerning surface effects on crack initiation and growth in polysilicon MEMS structures subjected to cyclic loading. Implications on the fatigue damage in silicon structures are discussed. The last contribution in this subtopic deals with aspects of contact mechanics in materials that can undergo phase transformations. Galanov, Domnich and Gogotsi propose a model to predict the transformed region in semiconductors and ceramics as a function of contact geometry.

*On-chip Testing of MEMS Devices* is highly desirable because the thin-film microstructure and state of residual stress is a strong function of microfabrication process steps. Espinosa, Zhu, Fischer and Hutchinson propose a methodology that combines a membrane deflection experiment and three-dimensional (3D) numerical simulations to identify Young's modulus and the residual stress state of free-standing films used in RF-MEMS switches. These authors show the relevance of modeling the initial film shape in the identification process. The accuracy and usefulness of measuring on-chip load-deflection signatures is demonstrated.

*Stress Waves in Thin Films* is highlighted in two papers. The paper by Fitzgerald, Kenny and Dauskardt reports on unique measurements of multiple microsecond duration crack arrests in the failure of micro-machined single-crystal silicon specimens. Using elastic wave propagation analysis, these authors conclude that arrest patterns are caused by the interference of boundary reflected stress waves with the propagating crack tip. Wang, Sottos and Weaver present a new test for mixed mode interfacial failure characterization of thin films. An interesting experimental setup consisting of laser generated waves and longitudinal wave conversion at an oblique surface is employed to examine delamination of an Al/fused silica interface. The authors report on significantly different post-mortem film morphologies, wrinkling and tearing, compared to those observed in similar films failed under dynamic tensile loading.

*Nanomaterials Testing* is an exciting but challenging area. One of the major difficulties is the manufacture of bulk samples of high quality, i.e., low porosity, uniform distribution of phases, etc. Barthelat, Wu, Prorok and Espinosa report on the investigation of dynamic failure of nanocrystalline coatings by employing a dynamic torsion experiment with high-speed photography and digital image correlation as diagnostic techniques. WC/Co coatings produced by high-velocity oxygen fuel spraying on a ductile substrate were investigated. Mode III failure of the coating was observed and quantified in real time. Another interesting experimental technique to identify strain fields in the micro range is presented by Sciammarella, Sciammarella, and Kim. Computer-aided Moiré is employed to investigate size scale effects in the plasticity and fracture of composites. Processing and characterization of epoxy/clay nanocomposites is reported by Daniel et al. By employing transmission electron microscopy (TEM) and X-ray diffraction, these authors assess the role of manufacturing parameters on the achieved degree of exfoliation and dispersion of the 1 nm thick clay layers. Stiffness increases of up to 50% with respect to unfilled epoxy are measured with a clay concentration of just 5%. Micromechanical modeling of the behavior of nanocomposites is also discussed.

*Biomaterials Functional Modeling* is a very stimulating area of research because of the exquisite and sophisticated behavior encountered in nature. Two very interesting papers are presented in this area. The paper by Spector and Jean deals with the estimation of elastic moduli of the outer hair cell composite membrane. Outer hair cells are piezoelectric biomaterials responsible for the conversion and amplification of sound waves into electrical pulses. The authors contend that proper identification of elastic moduli is key to the understanding of this phenomenon. The last paper in the volume deals with modeling in experimental biology. In the fields of genomics and neuroscience, the large amounts of information gathered on the functionality of biomaterials, e.g., gene expression, protein function, and cellular synapses, present an extremely complex computational problem. Wiggins and Nemenman present a numerical technique based on time series analysis for inferring process pathways. The technique is particularly promising to investigate parameter sensitivity and microscopic parameters appearing in the formulation of theoretical models.

The guest editor hopes that this publication of current and ongoing research will provide valuable insight, excitement and perspective to a wide range of researchers and design engineers with an interest in the general areas of thin-film mechanics, MEMS and nanomaterials.

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