Simultaneous imaging of the topography and dynamic properties of nanomechanical systems by optical beam deflection microscopy

P. M. Kosaka, J. Tamayo, E. Gil-Santos, J. Mertens, V. Pini, N. F. Martínez, O. Ahumada, and M. Calleja

1Instituto de Microeléctronica de Madrid, CSIC, Isaac Newton 8 (PTM), Tres Cantos, 28760 Madrid, Spain
2MecWins, Santiago Grisolía 2 (PTM), Tres Cantos, 28760 Madrid, Spain

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We present an optical microscopy technique based on the scanning of a laser beam across the surface of a sample and the measurement of the deflection of the reflected laser beam in two dimensions. The technique is intended for characterization of nanomechanical systems. It provides the height of a nanomechanical system with sub-nanometer vertical resolution. In addition, it simultaneously provides a complete map of the resonant properties. We demonstrate the capability of the technique by analyzing the residual stress and vibration mode shape of a system consisting of two elastically coupled nanocantilevers. The technique is simple, allows imaging in air, vacuum and liquids, and it is unique in providing synchronized information of the static and dynamic out-of-plane displacement of nanomechanical systems. © 2011 American Institute of Physics.

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I. INTRODUCTION

The miniaturization of mechanical devices to the micro- and nanoscale, referred to as nanomechanical systems (NMSs),1–3 has enabled advanced scanning probe technologies,4 ultrasensitive mechanical sensors,5,6 and promises to have a substantial impact on electronics and energy generation.7 The potential of nanomechanical systems, often shaped as tiny diving boards, rely on that their nanometer-scale displacement and vibration are highly sensitive to external forces, in-plane surface forces and added mass. These attributes imply that NMSs combined with either optical or electrical displacement sensors can be applied for measuring the force between two molecules or atoms with attonewton sensitivity.4,5 weighing the mass of a deposited molecule with zeptogram sensitivity6–8 and simultaneously measuring its elastic stiffness with kPa resolution.9,10 and for the label-free detection of molecular recognition on the NMS surface via the generated in-plane forces.11–13

The performance of a NMS critically depends on its spring constants, residual strain/stress, resonance frequencies, mechanical losses and vibration mode shapes. Most of these parameters can be predicted by finite element simulations. However, these simulations often require substantial amounts of computer and user time to obtain accurate solutions. In addition, misleading results are obtained if the underlying mechanics of the problem is not well understood. On the other hand, microfabrication and nanofabrication processes inherently introduce geometry imperfections, dislocations and residual stress and strain that can significantly modify the expected mechanical response.14 Hence, noninvasive optical tools for the characterization of the mechanical properties is becoming a need to obtain reliable results with nanomechanical systems and for the validation of micro- and nanofabrication processes.15 Recently scanning Doppler laser vibrometry (SDLV) and white light optical interferometry (WLI) have demonstrated a significant ability for the characterization of nanomechanical systems. SDLV can image high sensitivity the out-of-plane vibration of nanomechanical systems with submicrometer lateral resolution.20 WLI provides information on the topography of nanomechanical systems with a vertical resolution of 1–10 nm.21,22

II. EXPERIMENTAL SETUP

The core of the technique is the automated two-dimensional scanning of a laser beam across the surface of a nanomechanical system and the collection of the reflected beam on the surface of a two-dimensional position sensing linear detector (PSD) orthogonally oriented to the reflected beam [Fig. 1(a)]. We define a coordinate system in which the X-Y plane is the device plane and X and Y are along the scanning directions. Hence the out-of-plane displacement of the nanomechanical system is along the Z axis. The incident laser beam is in the X–Z plane and the PSD is oriented with one axis along the Y direction. In this configuration, the photocurrents along the PSD axes are linearly proportional to the slope of the device along the X and Y directions at the point of reflection [Figs. 1(b) and 1(c)]. Since the photocurrents are normalized with respect to the total photocurrent, the slope values are insensitive to intensity fluctuations and variations in the optical properties of the surface. After the scanning of the region of interest, the raw data consist of a two-dimensional map of the reflected intensity and the

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The surface normal vector obtained from the slope data pairs. To reconstruct the surface of the object under study, we define a mask based on the reflected light intensity that provides the shape of the object. Then we adopt an iterative integration method used for image reconstruction in photometric stereo to calculate the height of the object from the normal vector data. The technique was applied to characterize a nanomechanical system that consists of two nominally identical silicon nitride (SiN) nanocantilevers, elastically coupled by an overhang at their bases [Figs. 1(d) and 1(e)]. The length, width, and thickness of each cantilever are 25 μm, 10 μm, and 100 nm, respectively. The gap between the cantilevers is 60 μm and the overhang is 25 μm long. Gold sensing regions with an area of 10 × 10 μm² and thickness of 25 nm were placed at the cantilever free ends. The Au regions are intended for functionalization with biological receptors in biosensing assays. The position at the free cantilever end maximizes the mass sensitivity of the assay. In contrast with most of nanomechanical mass sensors that use the resonance frequency shift, this device uses the vibration localization produced by the differential mass adsorption on the two cantilevers. These devices possess common mode rejection, i.e., vibration localization is almost insensitive to nonspecific adsorption, which is crucial for selective biosensing experiments. We have chosen this system to challenge our technique due to the small size of the nanocantilevers, their low reflectivity, and the complex dynamic response. Moreover, the Au regions add the difficulty of having a device with different materials, and therefore heterogeneous optical properties.

III. RESULTS AND DISCUSSION

Figure 2(a) shows the image of the static out-of-plane displacement of the coupled cantilevers. The spatial lateral resolution in this case was of about 2–3 μm. The residual surface stress is located at the regions with higher curvature, which can be clearly observed in the cross-sections along and across the coupled cantilevers shown in Figs. 2(b) and 2(c). In these devices, most of the residual stress arises from the SiN that is deposited on a SiO₂ layer by low pressure chemical vapor deposition (LPCVD) during the fabrication process. These LPCVD films have a tensile stress of about 200 MPa that makes the cantilevers bend upwards when they are released. In addition, the difference in stress between the Au areas and the SiN makes that the cantilever free ends bend downwards.

At this point, it is useful to compare our technique with WLI, the reference optical technique to measure surface topography. A primary difference is that our technique...
different environments, these compensators must be made has recently used optical path compensators for measuring in atomic force microscopes. Although, WLI measurements in gas, liquid, and vacuum as it has been widely beam deflection technique can be easily adapted for measure- ration is of about 10^{-5} nm/Hz^{1/2}, at least two orders of magnitude better than in WLI.24 Finally, but not less important, the beam deflection technique is nearly insensitive to refraction and reflectivity variations of the surface that provide significant height errors in WLI.19 Thereby, WLI in our devices gives a false step of 300 nm (Fig. 3) between the chip and the suspended nanomechanical structure.

directly measures height gradients, whereas WLI measures differences in the optical path between a reference mirror and the sample. Therefore, our technique is not sensitive to sharp height steps. For instance, the step due to the 25 nm thick Au regions on the cantilevers cannot be observed. However, the beam deflection technique is nearly insensitive to refraction and reflectivity variations of the surface that provide significant height errors in WLI. Moreover, the refraction index depends on the strain, and hence WLI can provide significant height errors in very strained structures. Another advantage of the beam deflection technique is that the vertical resolution is of about 10^{-3} nm/Hz^{1/2}, at least two orders of magnitude better than in WLI. Finally, but not less important, the beam deflection technique can be easily adapted for measurements in gas, liquid, and vacuum as it has been widely demonstrated in atomic force microscopes. Although, WLI has recently used optical path compensators for measuring in different environments, these compensators must be made ad-hoc for each fluid cell and encapsulation design, making the measurements time-consuming and relatively complex.

To study the dynamic behavior of the coupled nanomechanical system, we previously measured the frequency spectra of the thermomechanical fluctuation when the laser beam is focused on the cantilever’ tips (Fig. 4). The frequency spectra exhibits two resonant peaks at the same frequencies in the two cantilevers, 42.3 and 50.1 kHz. The vibration modes corresponding with these frequencies are referred to as slow (s) and fast (f) vibration modes. The quality factor is low, about 11, due to the viscous damping in air. A priori, the fundamental mode in such a coupled system splits into a symmetric mode and an antisymmetric mode at a slightly higher frequency as shown in Fig. 4. The symmetric vibration mode consists of the two cantilevers flexurally vibrating in phase, whereas in the antisymmetric mode the cantilevers flexurally vibrate in antiphase.28,29 Notice that the amplitude of the s-mode is higher on cantilever 2 than in cantilever 1; whereas the opposite occurs in the f-mode (cantilever numbering is specified in the inset of Fig. 4). In coupled nanomechanical systems with identical cantilevers, the amplitudes of each vibration mode are the same in the two cantilevers, i.e., the vibration is spatially delocalized. In analogy to the Anderson localization phenomena, a small imperfection makes that the vibration localize.28,29 In our case, the found amplitude difference is consistent with cantilever 2 having a mass slightly higher than cantilever 1.

To obtain the amplitudes of the vibration modes at these two eigenfrequencies, we applied a frequency sweep voltage signal across a piezoelectric bimorph placed near the cantilevers’ bases. The sweeping signal, sample scanning and acquisi- tion of the PSD signal were synchronized and performed at each point in 10 ms. Figures 5(a) and 5(b) show the vibration-shape of the s and f vibration modes, respec- tively. The s vibration mode consists of the two cantilevers flexurally vibrating in phase, which is the well-established symmetric mode found in coupled cantilevers [see cross-sec- tions along and across the cantilevers in Figs. 5(e) and 5(e)]. Strikingly, the amplitude begins to decrease at the Au areas. In the f vibration mode, the cantilevers vibrate in antiphase. However, the vibration mode differs from the standard antisymmetric mode in which the cantilevers vibrate in antiphase in a flexural way. Here the opposite overhang edges twist in antiphase. This vibration transmits to the cantilevers that initially follow the twisting motion of the overhang until the Au region where the twisting motion changes of sign around the Au region. The flexural and torsional features of this vibration mode can be more clearly observed in the longi- tudinal and transversal cross-sections [Figs. 5(d) and 5(f)]. The major complexity of the vibration modes with respect to

FIG. 3. (Color online) Comparison between the longitudinal profile of one of the cantilevers shown in Fig. 2 by the scanning beam deflection technique presented here (thick continuous line, SBD) and white light interferometry (dashed black line, WLI). WLI gives a false step between the chip and the suspended nanomechanical structure.

FIG. 4. (Color online) Frequency spectra of the thermomechanical noise of the coupled nanocantilevers. The inset shows the height image of the system as shown in Fig. 2 for the identification of the cantilevers. The cantilevers at the left and the right are identified as 1 and 2, respectively. The observed two resonance peaks are referred to as s-mode (at lower frequency) and f-mode (at higher frequency).
those previously found in coupled nanomechanical systems arise from the (1) the significant residual stress of the SiN and large stress gradient across the thickness in the Au-coated areas (2) the large size of the overhang that mechanically couples the cantilevers and (3) the higher flexural rigidity and linear mass density at the free ends as a consequence of the Au coating.

The dynamic characterization of nanomechanical systems by the presented technique surpasses several limitations of stroboscopic WLI that have been described above in the topography characterization. In addition, stroboscopic WLI requires of 1–2 hs to characterize a typical frequency spectra of a NMS due to the large number of images required to obtain this information, whereas the presented technique performs this characterization in few relevant active point of the NMS in less than one second. Notice that this characterization step is needed before the acquisition of the vibration image of the NMS. On the other hand, our technique has capabilities similar to those of SLDV that is the reference technique for mapping out-of-plane vibration of NMSs. These capabilities include a vibration resolution of about 0.01 nm and a lateral spatial resolution between 0.5 and few micrometers. The advantage of SLDV is its sensitivity to vibration components that involve rigid motion without bending. These motions do not induce height gradient variations, and cannot be detected by the technique presented here. However, SLDV does not provide static information, whereas our technique simultaneously provides topography and dynamic information. This feature is really useful to link the residual stress with the resonant behavior as demonstrated in the present application. In addition, our technique can be easily implemented for measurements in liquids.

IV. CONCLUSIONS

In conclusion, we have developed a technique for the simultaneous characterization of the topography and dynamic behavior of nanomechanical systems. The technique is simple and significantly enhances some of the features of the current optical techniques.

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