Determination of Residual Stress in Ultrathin Atomic Layer Deposition Films Using Curved Nanobeams

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Owing to its monolayer level thickness control, superior conformality, tunable film composition with a large number of materials, and pinhole-free nature, atomic layer deposition (ALD) continues to be highly utilized in numerous technological applications such as semiconductor and photovoltaic devices. Continued scaling and miniaturization of these nanoscale devices has led to ALD films being deposited at single-digit nanometer thicknesses. As with all thin films, residual stress in ultrathin ALD films can significantly affect device performance and reliability. Currently, characterization of residual stress in these ultrathin films is challenging and is predominantly achieved by high resolution measurements of lattice strain using transmission electron microscopy which is a destructive, low-throughput technique requiring specialized tools and knowledge.

With our work, we present a quantitative methodology for the localized, nondestructive, in-situ measurement of residual stress in conformal ultrathin films obtained using ALD. Our remarkably sensitive technique, which utilizes a highly compliant, curved nanobeam suspended structure fabricated using a silicon on insulator (SOI) wafer, assesses the film's residual stress by comparing the difference in the static in-plane deflection of the nanobeam's midpoint before and after the application of the ALD film as highlighted in Fig. 1. Using the formalism of Euler-Bernoulli beam theory and the Galerkin method, we have developed a theoretical model to generate analytical expressions for the residual stress in the ALD film and underlying device layer. These analytical expressions have been further justified by modeling our devices using finite element methods. Since the curved nanobeams have an asymmetric buckling configuration, both tensile and compressive stress can be analyzed, thereby not limiting applicability to certain ALD films. We have experimentally demonstrated our approach using standard ALD films including aluminum oxide (alumina, Al_2O_3), hafnium oxide (hafnia, HfO_2), and platinum (Pt). Furthermore, as shown in Fig. 2, our method requires only three scanning electron microscopy (SEM) images to acquire the necessary deflection data, which enables multiple nanobeams to be analyzed rapidly. We provide one example of such an analysis, as illustrated in Fig. 2d, showing the distribution of residual stress for an $\approx$11.7 nm thick ALD alumina film from 90 devices.

We envision that our ultrathin ALD film characterization technique will be widely applicable to a variety of situations including strain engineering of transistors and high-κ dielectrics in the semiconductor industry, to the tuning of optical, magnetic, and electrical properties in MEMS/NEMS structures, and to the high-throughput characterization of ultrathin multifilm stacks or full-wafer mapping using today's automated and parallelized SEM systems.

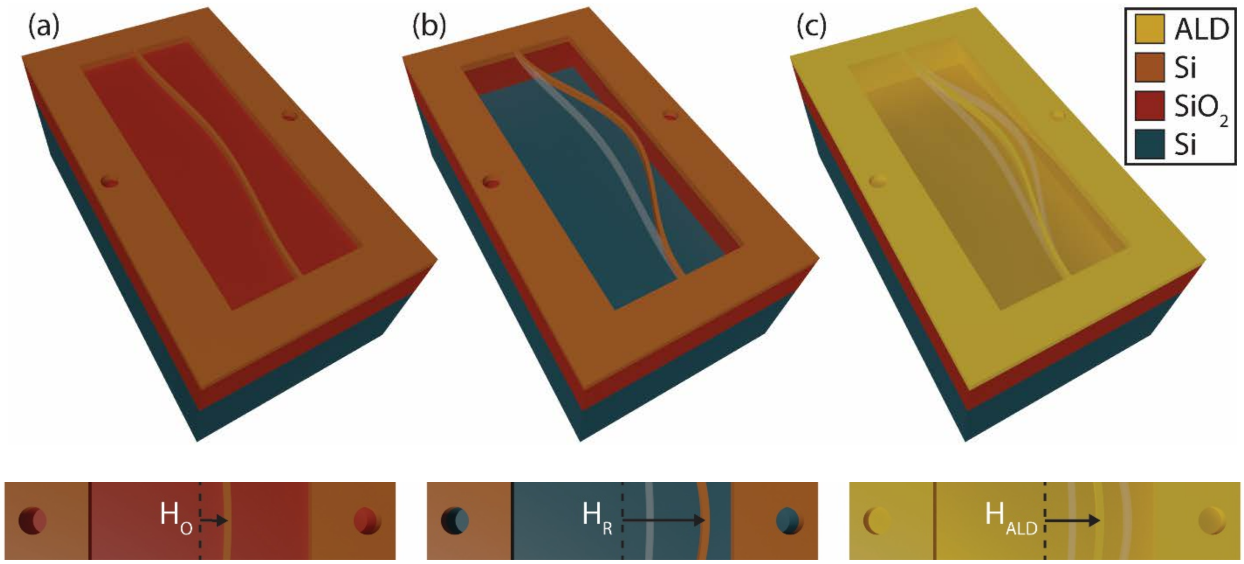

FIG. 1. Illustration of the curved nanobeam device and the measurement procedure. (a) Initial midpoint deflection of the beam's centerline, H_O, which is lithographically defined by electron-beam (e-beam) lithography. The two circles etched into the device layer on the periphery of the device are for pixel size calibration. (b) Midpoint deflection of the beam's centerline, H_R, after device release. (c) Midpoint deflection of the beam's centerline, H_{ALD}, after depositing the ALD film. Knowledge of H_O, H_R, and H_{ALD} enables the determination of the residual stress through analytical calculations. The transparent white beams in (b) and (c) signify previous beam placements. The dashed lines represent the midpoint between the two circles. Due to the orders of magnitude difference between various geometrical dimensions (e.g. beam length ≈ 40 μm, beam width ≈ 100 nm), the schematic does not provide an accurate representation of various device dimensions.

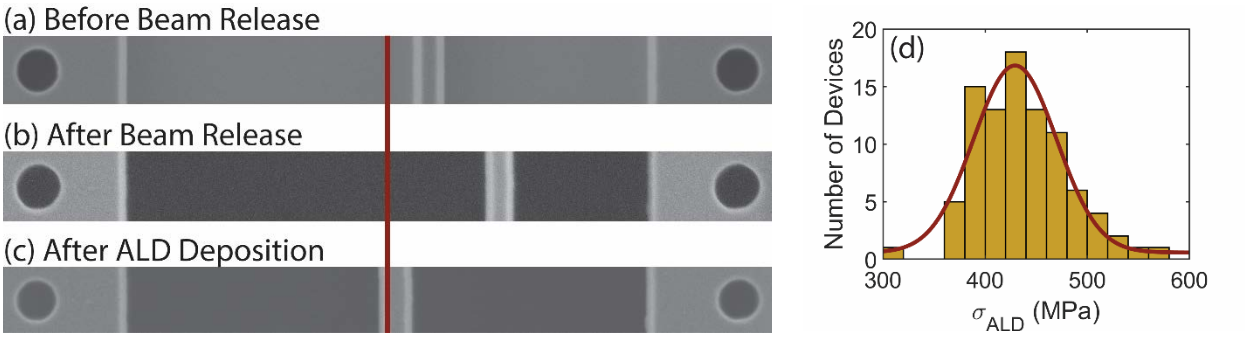

FIG. 2. SEM micrographs showing a curved nanobeam with a nominal length of 40 µm, a width of 100 nm, and a thickness of 250 nm. The images show the deflection of the nanobeam (a) prior to release, (b) after release, and (c) after approximately 11.7 nm of alumina was deposited using ALD. The red line denotes the midpoint between the two circles. (d) The distribution of residual stress from 90 devices with a mean stress of 429.2 MPa (tensile) and a standard deviation of 40.6 MPa.