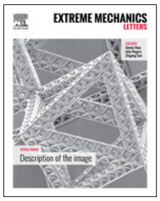
Extreme Mechanics Letters 1 (2014) 9–16

Contents lists available at ScienceDirect

Extreme Mechanics Letters

journal homepage: www.elsevier.com/locate/eml



Silicon nanomembranes as a means to evaluate stress evolution in deposited thin films

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ARTICLE INFO

Article history:
Received 21 November 2014
Received in revised form 3 December 2014
Accepted 3 December 2014
Available online 5 December 2014

Keywords:
Thin films
Silicon
Nanomaterials
Stress and strain
Nanomembranes

ABSTRACT

Thin-film deposition on ultra-thin substrates poses unique challenges because of the potential for a dynamic response to the film stress during deposition. While theoretical studies have investigated film stress related changes in bulk substrates, little has been done to learn how stress might evolve in a film growing on a compliant substrate. We use silicon nanomembranes (SiNMs), extremely thin sheets of single-crystalline Si, as a substrate for the growth of amorphous SiN_x to begin to address this question. Nanomembranes are released from a silicon-on-insulator wafer with selective etching, transferred over a hole etched into a Si wafer, and bonded to the edges of the hole. The nanomembrane window provides the substrate for SiN_x deposition and a platform, using Raman spectroscopy, for measurements of the evolving strain in the nanomembrane. From the strain in the nanomembrane, the film stress can be inferred from the required balance of forces in the film/substrate system. We observe that the strain in the tethered NM increases as the NM is made thinner while the intrinsic steady-state stress in the deposited film is reduced.

1. Introduction

Thin-film deposition on thick substrates is widely used and has been extensively investigated. The stress that forms in these systems can be characterized and quantified by classical analysis [1,2] of the physical effect the film has on the substrate (*e.g.*, bending, cracking, *etc.*). In modern applications, substrates may, however, be quite thin. One may expect that the stress in a thin film deposited on a thin substrate will evolve differently from that of a similar film deposited on a thick substrate, because in such systems the strain can be shared during deposition [3]. Silicon nanomembranes (NMs), thin sheets of single-crystalline Si, potentially provide the platform to investigate such stress evolution [4], because the Raman spectrum in Si is very sensitive to strain [5,6]. Eventually one would hope to use a thin crystalline Si sheet as a strain gauge to evaluate the stress in a film at various stages in the deposition, from that determine if the stress in the film builds up differently if it is grown on a thick or a thin substrate, and thereby begin to understand better stress evolution during the growth of thin films.

Semiconductor nanomembranes have evolved in the last decade into a major platform for both fundamental

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http://dx.doi.org/10.1016/j.eml.2014.12.003

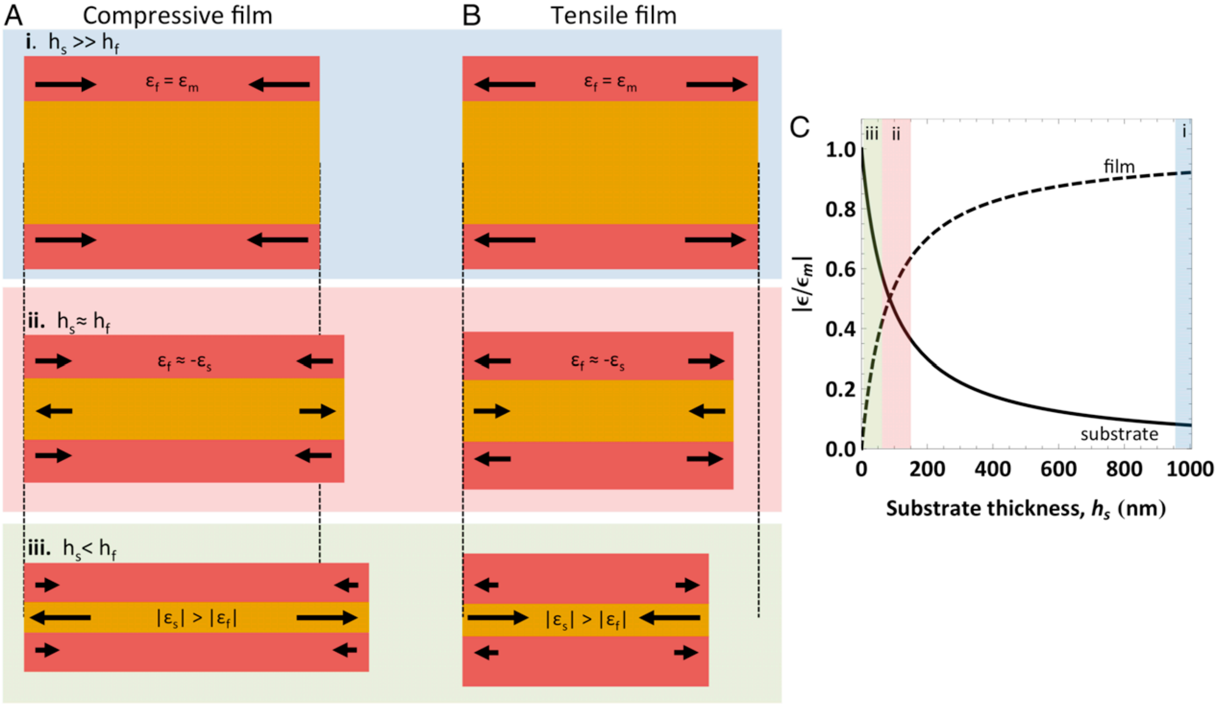

Fig. 1. Illustration of strain sharing between a film and substrate as the substrate is thinned. Initially, all the strain in the system is in the film (i). As the substrate is thinned, some of the strain is transferred to the substrate (ii). Once the substrate is thinner than the total film thickness the strain magnitude in the substrate exceeds that in the film (iii). (A) Compressive strain in the film is transferred as tensile strain to the substrate. (B) Tensile strain in the film is transferred as compressive strain to the substrate. The schematic diagrams in (A) and (B) show a film deposited on both sides of the substrate such that the bending moment can be neglected. (C) Plot of the normalized strain magnitude. The elastic properties of film and substrate are assumed equal ($M_f = M_s$) and the total film thickness (sum of top and bottom films), h_f, is constant at 100 nm.

studies and novel device applications [7–10], with a major driving force being the application of or the response to strain. In the pursuit of new physical properties, Group IV NMs have been strained in a controlled manner, among others, to modify the band structure or band offsets [11,12], to change the strain symmetry [13], or to create improved two-dimensional electron gases [14,15]. In the pursuit of nanoarchitectures or new devices, Group IV NMs have been rolled into tubes [10,16–18] or supported channels [19]; or bonded to flexible supports [7,20–24] or curved surfaces [25] for electronic- and optoelectronic-device applications.

For growth on thin substrates, strain sharing [3,4] has been observed for the epitaxy of nanocrystals on SiNMs [26–28]. In these systems, the strain transfer was analyzed by modeling the local and global bending of the NM. Here we investigate deposition of an amorphous, presumably continuous, compressive silicon nitride (SiN_x) film, and use Raman spectroscopy as the major tool to analyze strain, and thus stress in the deposited film.

1.1. *Stress–strain relationships in thin films*

In conventional thin-film deposition on thick, rigid substrates (thickness of substrate, $h_s \gg$ thickness of film, h_f), as long as the film adheres to the substrate, the stress in the film is inferred from the resulting curvature of the substrate. Stoney's equation [1] relates the curvature of the substrate, κ, to the physical properties of the substrate (biaxial modulus, M_s, and thickness, h_s), the thickness of the film, h_f, and the stress in the film, σ_f:

$$\kappa = \frac{6\sigma_f h_f}{M_s h_s^2}. \tag{1}$$

Because it is assumed that the substrate is much thicker than the film ($h_s \gg h_f$), effectively all the elastic *strain* in the system is in the film. The elastic strain in the film, ε_f, is related to the film stress by the biaxial modulus of the film ($\varepsilon_f = \sigma_f / M_f$). The strain in the system is defined as the difference between the strain in the film and the strain in the substrate, $\varepsilon_m \equiv \varepsilon_f - \varepsilon_s$. Therefore, when $h_s \gg h_f$, $\varepsilon_m = \varepsilon_f$.

If the substrate thickness is reduced such that h_s is no longer much larger than h_f, the total strain in the system is shared between the film and the substrate. The system as a whole will expand or contract (and curl) according to the system strain [3,10]. To illustrate this concept, consider a thin film with some strain, ε_f, grown on a bulk substrate such that initially $\varepsilon_m = \varepsilon_f$. Fig. 1 shows a film grown on both sides of the substrate so that curvature in the system can be ignored: bending moments from either side of the substrate cancel each other such that only expansion or compression of the system needs to be considered. If one then imagines that the substrate is thinned (even though that is not experimentally possible with a film on both sides), some of the system strain, ε_m, is transferred to the substrate. Now the system strain is shared between the film layers and the substrate ($\varepsilon_m = \varepsilon_f - \varepsilon_s$). Using this