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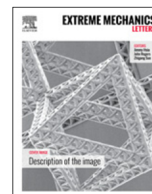

Stress analysis for nanomembranes under stamp compression

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ABSTRACT

Many high performance flexible and stretchable electronics are manufactured by transferring inorganic semiconductor nanomembranes from their rigid donor substrates to soft receiving substrates via elastomeric rubber stamps. As nanomembrane thickness reduces to nanometers or subnanometers (e.g., 2D materials), they can be easily ruptured during the stamping process by shear stresses. Through analytical modeling, this paper reveals the membrane stress in the nanomembrane induced by stamp compression as a function of the stamp and nanomembrane property and geometry, as well as the traction–separation relation between the nanomembrane and the donor substrate. While membrane stress in the nanomembrane increases monotonically with the compressive loading applied on the stamp, an abrupt increase appears when nanomembrane–substrate interface starts to fail. While the stamp is assumed to be incompressible material in the main text, more general solutions for compressible stamps are offered in the supplementary material (see Appendix B).

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1. Introduction

Inorganic semiconductors such as silicon (Si), gallium arsenide (GaAs), and gallium nitride (GaN) are, by far, the most well-established materials for high performance electronics and optoelectronics. Although these materials are intrinsically rigid and brittle, when exploited in mechanically optimized layouts, they can be integrated on soft polymer supports to yield integrated flexible or stretchable functional devices. The result is an electronics/optoelectronics technology that offers the performance of conventional wafer-based systems, but with the mechanics of a piece of paper or a rubber band. Examples include flexible displays [1], solar cells [2,3], stretchable optoelectronics [4] and photovoltaics [5], as well as bio-inspired [6,7] and bio-integrated [8–10] electronics.

Semiconductors in these examples are in the form of nanomembranes (NMs) and nanoribbons (NRs) due to their ultra-low flexural rigidities and small strains even when bent or buckled to small radii of curvature. Since high quality crystalline NMs are usually formed by wafer bonding and polishing or controlled fracture [11], or by epitaxial growth on crystalline substrates [3,12], they need to be integrated onto substrates of choice in a controlled, deterministic fashion by the techniques of transfer printing [13–15]. An important feature of this process is that it exploits the known, lithographically defined positions and orientations of undercut-etched nanostructures. As a common example, Si NMs can be formed by releasing the top Si layer of a silicon-on-insulator (SOI) substrate

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after etching away the buried oxide layer with hydrofluoric acid [16,17]. Other SOI-like structures that can serve as routes to different semiconductor nanomaterials include germanium-on-insulator (GOI), silicon–germanium-on-insulator (SGOI), as well as III–V semiconductors and many other combinations [18–21]. Retrieval from these predetermined sites, followed by release onto other substrates, can be accomplished with rubber stamps such as the polydimethylsiloxane (PDMS). The procedure involves switching the strength of adhesion between these structures and PDMS from strong to weak states by exploiting viscoelastic and/or geometric effects [13,14,22,23].

Although transfer printing has been proved effective for many semiconductor NMs, the difficulty escalates when NM thickness drops below 100 nm, which gains optical transparency [24] and biodegradability [25] in the case of Si NM. Cracks and wrinkles easily form in ultrathin NMs picked up by PDMS stamps from our own experimental experience. This is why transparent thin film transistors (TFTs) based on Si NMs have been rarely reported and state-of-the-art transient or biodegradable electronics [26,27] are still using Si NMs with thickness in the hundreds of nanometers regime. Similar problems exist when peeling or exfoliating nanometer or subnamometer thick two-dimensional (2D) atomic layers using PDMS stamps. In our recent paper [28], few layer molybdenum disulfide (MoS_2) flakes were exfoliated from a synthetic MoS_2 crystal by either adhesive tapes or PDMS stamps. In either case, cracks, wrinkles, and buckle delaminations are clearly visible in exfoliated samples.

So far, the cause of failure when stamping on ultrathin NMs remains unclear and it hence lacks a guideline for minimizing stamping induced NM failure. To tackle this problem, we decide to first find out the stamp–NM interaction and then set up a boundary value problem (BVP) to solve for the membrane stress developed in the NM, as described in Section 2. Our results reveal that the compressive load applied on the stamp plays a significant role. The size and mechanical properties of the stamp can affect the stamp–NM interaction and can be used to tilt the membrane stress to avoid cracking. Results are summarized in Section 3 and discussed in Section 4 with manufacturing guidelines provided.

2. Boundary value problem

The stamping process with an unstructured, flat stamp is illustrated by cross-sectional schematics in Fig. 1(a) and (b). First, the PDMS stamp backed by a rigid layer (e.g., a glass slide) is making a gentle contact on the NM which is sitting on its donor substrate (e.g., Si NM on undercut oxide or chemical vapor deposited (CVD) graphene on seed copper (Cu)) (Fig. 1(a)). Then an external compression characterized by the compressive strain ϵ is applied to the stamp to form an intimate contact with the NM such that the NM can later be peeled off from the donor substrate by the stamp. Due to the Poisson's effect, the vertically compressed stamp would expand laterally, resulting in shear stresses on the stamp–NM interface [29–31], which rubs the NM and may eventually lead to cracked NM (Fig. 1(b)).

Assuming the stamp is an infinitely long strip into the paper, Fig. 1(c) draws the stresses experienced by the NM in a 2D plane strain model. The shear stress applied by the stamp on the top surface of the NM is labeled as τ_{top} whereas the shear stress applied by the donor substrate on the bottom surface of the NM is labeled as τ_{bottom}. A free body diagram (FBD) for the boxed part of the NM is provided as an inset in Fig. 1(c), which suggests that the edge on the right is a traction free surface while the membrane stress in the NM at the cut can be given by the equilibrium condition:

$$\sigma(x) = \frac{\int_x^a \left(\tau_{top}(\eta) - \tau_{bottom}(\eta)\right) d\eta}{h_m} \tag{1}$$

where x starts form the middle of the NM (Fig. 1(a)), a is the half size of the stamp and NM and h_m is the thickness of the NM. Eq. (1) offers a simple explanation why ultrathin NMs are more prone to fracture during stamping: as the membrane stress is inversely proportional to the NM thickness, when NM thickness drops from hundreds of nanometers to few nanometers, the membrane stress can be elevated by hundred times. Given h_m, the central goal of this paper is to quantify $\sigma(x)$ as a function of the stamp geometry and property, the NM–substrate interface property, as well as the compressive load ϵ applied on the stamp.

τ_{bottom} is the shear stress developed to balance τ_{top}. Before discussing τ_{top}, we assume that the evolution of τ_{bottom} has to follow the shear traction–separation relation (TSR) along the NM–substrate interface. Various TSRs have been developed and applied to describe physical phenomena of interface fracture. For simplicity, a rectangular TSR as shown in Fig. 1(d) is adopted, where τ_0 is the NM–substrate interface adhesion strength, δ_c is the critical separation between NM and substrate, and the area within this rectangle is the interface adhesion energy. As the substrate is assumed rigid and non-deformable, separation between the NM and the substrate is identical to the NM displacement in the x direction, $u(x)$. Whenever $|u(x)|$ exceeds δ_c, the NM will fully and permanently detach from the substrate at that point and there is no more interaction between them. Re-adhesion is not allowed in this model. Hence τ_{bottom}, a function of $u(x)$, could be written as

$$\tau_{bottom} = \begin{cases} 0 \sim \tau_0 & |u(x)| = 0 \\ \tau_0 & 0 < |u(x)| < \delta_c \\ 0 & |u(x)| \geq \delta_c. \end{cases} \tag{2}$$

τ_{top} captures the interaction between the stamp and the NM. Since the rubber stamp is sandwiched between the rigid backing layer and the rigid NM-on-substrate and the bottom of the stamp can be assumed fixed due to minimum deformation in both the lateral and vertical direction of the stiff NM. Thus, we can adopt our previous solutions for an infinitely long elastic layer bonded and compressed between two rigid plates (Eqs. (44) and (48) in [29]):

$$\tau_{top}(x) = \epsilon A \sinh\left(\alpha \frac{x}{h}\right) \tag{3}$$

where A and α, determined by the mechanical properties and geometry of the stamp, are given by the following equations

$$A = \frac{\alpha \nu E}{2(1+\nu)(1-2\nu)\cosh\left(\frac{\alpha a}{h}\right)} \tag{4}$$

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