Monan Ma

monan@bu.edu

This postdoctoral research proposal serves as a writing sample to reflect my research background, how I formulate a research problem, and career goals. Specific project directions are flexible and are intended to be adapted in collaboration with the lab PI. No AI was used to create this proposal.

Nanoelectromechanical Systems with Tunable Nonlinear Properties

Nanometer-scale mechanical structures, such as nanoprinted metamaterials [1, 2], graphene-based resonators [3], nanomechanical beams [4] and cantilevers [5], exhibit inherent nonlinear dynamics. The nonlinearities in these systems primarily arise from intrinsic factors, such as material nonlinearities [6], energy dissipation [7], and nonlinear stiffening due to geometric effects [8]. Nonlinear effects can also emerge from external sources, such as integrated transducers [9].

Current problem. With some notable exceptions [10], nonlinear effects in micro- and nanoscale systems have generally been intentionally avoided rather than exploited. This is because the emergence of nonlinear effects introduces instabilities in a system, such as amplitude and frequency jumps [8], which are detrimental for engineered systems. However, when carefully isolated and characterized, nonlinear properties can be utilized in numerous societal and scientific applications, *e.g.,* resolution enhancement in mass spectrometry and atomic force microscopy [5], mechanical computing in extreme conditions [11, 12], nonlinear energy harvesting [13], impact absorption [14], and ultrasensitive signal transduction via parametric amplification [15].

Proposed solution. I am interested in exploring the design and characterization of nonlinear mechanical nanostructures with tunable properties by utilizing a synergistic combination of fabrication techniques, experiments, and numerical simulations. More specifically, I plan to develop a working pipeline for characterizing a resonating nanomechanical structure with a simple geometry, such as a doubly clamped beam, and bring it to the cusp of buckling. I will conduct experiments to investigate the improvement in sensing resolution for this critical state. Informed by numerical simulations and utilizing beam experiments as the foundation, I will explore options to scale up, such as custom-designed metamaterials or morphable microstructures that exhibit anisotropic or effective nonlinear properties. *Although buckling nanomechanical structures have been fabricated using nanolithography [16], nanoprinting a controllable buckling nanostructure and using the cusp of the buckling state as the detection regime has not yet been explored.*

Electrostatically controlled buckling in a 3D printed nanomechanical beam. Previous experimental realizations of buckling nanomechanical beams were primarily based on thermal expansion and electrostatic compression. However, the thermal expansion method often involves heating the structure by $\gtrsim 10$ K, which significantly decreases the quality factor of the beam resonator and is generally undesired for sensing applications.

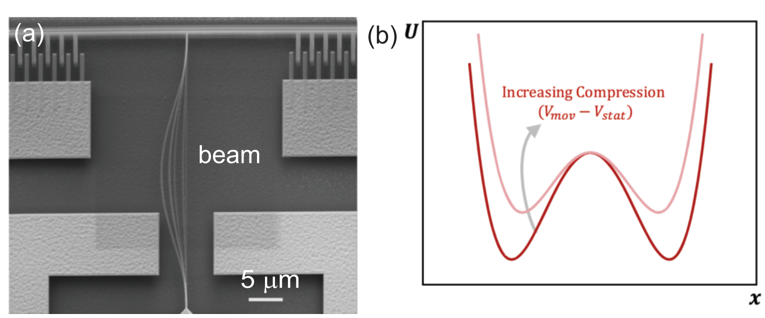

Figure 1: (a) SEM image of a buckling nanomechanical beam resonator with dimensions of $l \times w \times t = 40\ \mu\mathrm{m} \times 250\ \mathrm{nm} \times 150\ \mathrm{nm}$. (b) Potential well of the beam under buckling. The well becomes shallow with compression.

In this project, I aim to design and manufacture a physical platform comprising a slender Euler-Bernoulli beam with integrated electrostatic (capacitive) transducers for initiating compression and controlling the buckling process. A representative system of an electrostatically buckled nanomechanical beam is adapted from [16] and shown in Fig. 1 (a). Here, the system consists of a buckling beam positioned vertically, an electrostatic comb drive actuator for mechanical compression (top of image), and side electric gates for control-

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monan@bu.edu

ling the buckling direction, which are positioned on either side of the beam. When a DC voltage is applied to the comb drive, the interdigitated electrodes will move and compress the beam due to electrostatic forces [17]. The side gates supply an inhomogeneous electric field, which pulls the dielectric beam with the dipole force. This actuation principle is based on electric field inhomogeneities and thus does not require metalization. It can also be used in reverse to detect the mechanical motion of the beam [17]. The system is fabricated using traditional CMOS (complementary metal-oxide-semiconductor) manufacturing techniques, *i.e.*, electron-beam lithography for the silicon substrate and thermal evaporation for the gold layer metalization. The beam is made of silicon and has linear dimensions of $l \times w \times t = 40\ \mu\mathrm{m} \times 250\ \mathrm{nm} \times 150\ \mathrm{nm}$. Several frames of gradual buckling of the beam are shown in Fig. 1(a).

Nanoprinting the beam and transducer. I will leverage the metal 3D printing technique using the two-photon polymerization to fabricate a doubly clamped beam and the supporting structure for transducers. The metallic layer of the comb drive and side gate transducers can be fabricated using, for instance, thermal evaporation. The beam need not be metalized. The goal is to develop a working recipe for nanoprinting that achieves consistent buckling performance. The smallest dimension in the system will be the beam thickness t. Given the printing layer thickness of $\sim 2\ \mu\mathrm{m}$, I will start with a 3-layer print, resulting in the beam thickness of $t \sim 5\ \mu\mathrm{m}$ due to overlap. I will explore several orientations and the resulting performance difference in experiments.

Experiments: dynamic characterization. To study the dynamics of the system, it is necessary to first drive the beam at one of its resonant modes and monitor the change in the displacement amplitude. Both the drive and detection can be accomplished using the side gate electrodes. To ensure the beam is constantly driven at its resonance despite environmental drifts, a phase-locked loop [18] will be incorporated. Then, by gradually increasing the DC voltage amplitude to the comb drive, the uniaxial compression force will increase. As the beam approaches the cusp of buckling, a significant increase in displacement amplitude may occur due to induced effective softening.

Turning to the potential well of the beam, shown schematically on Fig. 1(b), the depth of the well will rise as the beam undergoes compression. It would be fascinating to see whether one can achieve a critical buckling state, where the double-well potential begins to transform into a nearly flat well. In this critical state, even tiny forces, such as environmental perturbations from surrounding air molecules, may be significant enough to induce buckling or large-amplitude oscillations. As a result, *one might uncover the fundamental aspects of previously unexplored chaotic dynamics and nonlinear nanomechanics that can lead to substantial enhancements in resolution for nanomechanical sensing and mechanical computing.*

Furthermore, using the results from the nanoprinted buckling beam as a building block, one can scale up the system by nanoprinting an array of such structures and collectively or individually controlling the buckling state, effectively forming a shapeshifting metamaterial [19]. It will also be exciting to explore the gas sensing resolution of a critically buckled beam. Hydrogen gas, for example, can physically adsorb onto the polymeric surface of the beam, and the gas concentration can be measured via frequency shift induced by mass loading (*i.e.,* the vibrating mass), and compared with state-of-the-art sensing resolution.

Numerical simulations. Given the vast parameter space enabled by metal 3D printing for material and geometry, it is reasonable to optimize the design parameters using simulation. The literature [16] can serve as the starting reference. However, given the characteristics of nanoprinting, it may be necessary to tune parameters such as the geometry and gap distance between the gate electrodes and the beam to avoid transduction nonlinearities [17] and allow only for controllable, in-plane buckling. Ultimately, *I intend to leverage my numerical expertise to develop a multi-physics model that captures the beam's gradual transition to the buckling state and validate the model using experiments.* In terms of modeling tools, I have 7 years of experience in using COMSOL, but I would also be interested in incorporating an open-source finite-element software such as FEniCS, and making my model accessible for the research community.

Undergraduate and Graduate Student Involvement

Each component of the proposed project can be divided into smaller research tasks and auxiliary projects that can be assigned to students. For example, I could have students working on the fabrication and design component, the experiments and measurement component, and the numerical simulation and physics modeling component. These projects will be significant for the overall progress of the research and can be done in the summer as well as during the semester.

Project Timeline

This project is estimated to be finished within approximately 2 years. The intermediate milestones and estimated timeline are shown in Table 1.

Research milestone	Y1 Fall	Y1 Spring	Y2 Fall	Y2 Spring
Nanoprint beam and transducer	•	•		
Build drive and detection setup	•	•		
Buckling experiment		•	•	
Numerical models		•	•	•
3D-print advanced structure			•	•

Table 1: Timeline for the 2-year project

Transitioning from Postdoctoral Research to Faculty Member

I am interested in pursuing a career in academia. As a future faculty member, I envision building an experimental group that harnesses the power of computational and data-driven methods. I intend to achieve this goal by promoting both independent and collaborative research, as well as the development of teaching skills. I am confident that the experimental and computational work during my postdoctoral stage will allow me to establish independence and constitute a significant part of my future academic career.

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