

DESIGN, FABRICATION, AND APPLICATIONS OF ELECTROSTATICALLY BUCKLED NANOMECHANICAL SYSTEMS

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By
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DESIGN, FABRICATION, AND APPLICATIONS OF ELECTRO-
STATICALLY BUCKLED NANOMECHANICAL SYSTEMS

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August 2018

We certify that we have read this thesis and that in our opinion it is fully adequate,
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ABSTRACT

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August 2018

Buckling is an important resource for memory and sensing applications at the micro- and nano-scale. Although different approaches have been developed to access buckling, such as the use of pre-stressed beams or thermal heating, none of them can dynamically and precisely control the critical bifurcation parameter—the compressive stress on the nanobeam— while keeping the heat generation and power dissipation at levels acceptable for real-life applications. Here, we develop an all-electrostatic architecture to control the compressive force, as well as the direction and amount of buckling, without heat generation. The devices, consisting of contact pads, comb-drive and beam, have been fabricated on Silicon on Insulator (SOI) chip by using micro-/nano-fabrication techniques. With this architecture, we demonstrated fundamental aspects of device function and dynamics. By applying signal voltages as low as 0.5 V, we controlled the direction of buckling to store binary information. Lateral deflections as large as 12% of the beam length were achieved, allowing nanomechanical manipulations at large deformations. We performed fatigue tests on the device which showed no discernible damage even after 10,000 buckling cycles. By modulating the compressive stress and lateral electrostatic force acting on the beam, we tuned the potential energy barrier between the post-bifurcation stable states and observed persistent transitions between the states. The proposed architecture, in this work, opens avenues for developing DC-controlled multibit nanomechanical logic gates, nano-manipulators, switches, and for studying the relationship between entropy and information.

Keywords: Buckling, nanomechanics, nanobeam, comb-drive, micro/nanofabrication, electrostatic control, bifurcation.

ÖZET

ELEKTROSTATİK OLARAK BURKULAN NANOMEKANİK SİSTEMLERİN TASARIMI, FABRİKASYONU VE UYGULAMALARI

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Burkulma, mikro ve nano ölçekte bellek ve algılama uygulamaları için önemli bir olanaktır. Burkulma elde etmek için ön-gerilimli kiriş kullanmak ya da termal ısıtma gibi farklı yaklaşımlar geliştirilmiş olmasına rağmen bunlardan hiçbirisi ısı üretimini ve güç kaybını gerçek hayat uygulamalarına uygun seviyede tutarak kritik çatallanma parametresini -kirişe uygulanan sıkıştırıcı gerilim- dinamik ve kesin olarak kontrol edememektedir. Bu çalışmada, sıkıştırıcı kuvvetinin yanı sıra burkulma yönünü ve miktarını da ısı üretimi olmadan kontrol edebildiğimiz tamamen elektrostatik bir mimari geliştirdik. Temas bloğu, tarak sürücü ve kırıktan oluşan bu aygıtlar, mikro ve nano üretim teknikleri kullanılarak, yalıtkan üstü silikon (SOI) yongalar üzerinde üretilmiştir. Bu mimari ile aygıtın işlev ve dinamiklerinin temel yönlerini gösterdik. 0.5 V kadar düşük sinyal voltajları uygulayarak, ikili bilgiyi depolamak için burkulma yönünü kontrol ettik. Yüksek deformasyonlarda nanomekanik manipülasyonlara imkan veren, kiriş uzunluğunun yüzde 12'sine kadar ulaşabilen yanal yönelimler elde edildi. Uyguladığımız yorulma testleri, 10,000 burkulma döngüsünden sonra bile aygıt üzerinde fark edilebilir bir hasar oluşmadığını gösterdi. kiriş üzerine etki eden sıkıştırıcı gerilimi ve yanal elektrostatik kuvveti modüle ederek burkulma sonrası kararlı durumlar arasındaki potansiyel enerji bariyerini ayarladık ve bu durumlar arasındaki kararlı geçişleri gözlemledik. Bu çalışmada sunulan yapı, doğru akım (DC) kontrollü çoklu-bit nanomekanik mantık kapıları, nano-manipülatörler, siviçler geliştirmede ve entropi ile bilgi arasındaki ilişkiyi çalışmada yöntemler sunmaktadır.

Anahtar sözcükler: Burkulma, nanomekanik, nanokiriş, tarak sürücü, mikro/-nanofabrikasyon, elektrostatik kontrol, çatallanma.

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Chapter 1

Introduction

Nano-electromechanical systems (NEMS)[1, 2] are devices, which have mechanical response (bending, buckling, etc.) to electronical transduction, with at least one dimension is in sub-micron scale. NEMS field started with the studies done in 1996[3] and has been growing since then. The advantages of the nanoscale devices are having high resonance frequency (MHz, GHz)[4] which enables high sensitivity to detect and even identify nanoparticles[5], relatively high quality factors (Q) such as tens of thousands[6], low effective masses such as femtograms[7], and large integration density as large as 60000 devices/mm²[8]. Based on these advantages, researches conducted for NEMS technology branch to inertial imaging[5], gas sensing applications[8, 9, 10, 11], single molecule mass sensing[12], force sensing[13, 14], and mass spectroscopy (single protein[15], neutral particle[16]).

The advent of NEMS has opened promising new perspectives for the development of sensors[12, 15, 17, 14] and mechanical computers,[18, 19, 20, 21, 22, 23, 24, 25] owing in particular to their potential for high-speed operation, their scope for large-scale integration, and their robustness in harsh environments[25, 26] (e.g., high temperatures, and exposure to ionizing radiation and electromagnetic pulsation). In these applications, the use of buckling instability can increase the resolution of sensors,[27] decrease the footprint of micro-relays,[28] and reduce

the operational complexity of memory devices.[21, 29, 30, 31] Recently, buckling has also emerged as an important resource for controlling optomechanical dynamics;[32, 33] designing smart materials[34] such as morphable microelectronic devices,[35] non-reciprocal metamaterials[36] and energy harvesters;[37] and understanding the organization of cellular interfaces,[38] and wrinkling in aging and cerebellum development.[39, 40]

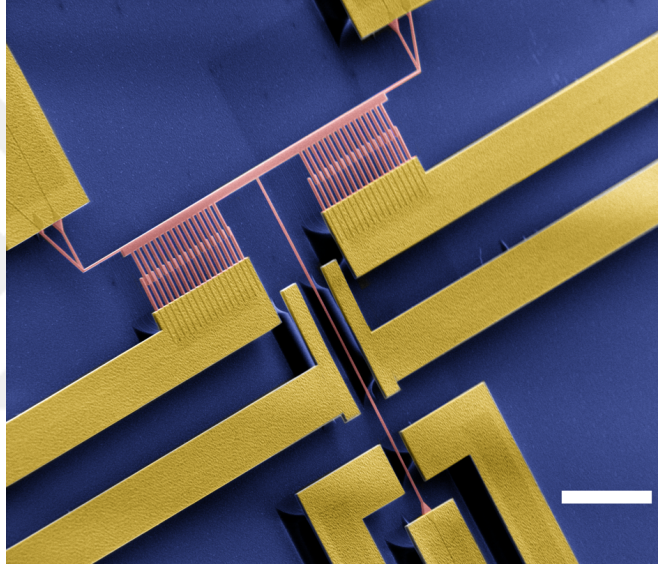


Figure 1.1: Example of a NEMS device fabricated for this study. Scale bar is 10 μm .

Despite the important role it plays in different applications, a precise, dynamical and all-electronic control of buckling bistability has been absent at the micro- and nano-scale. Buckling at this scale has often been accomplished by using prestressed beams;[29, 30] however, this approach is not suitable for the dynamical and precise control of the critical bifurcation parameter: the compressive stress on the beam. Another common approach has been to induce buckling thermally, which creates excessive amount of heating (temperature increase by tens of Kelvins) and power consumption ($\sim\text{mW/bit}$) for realistic applications.[21, 41]

The present study sought to address the above shortcomings by developing a technique for controlling the buckling parameters without significant heat generation and solely through the application of DC voltages. Proposed buckling

paradigm comprises no current flowing part (other than the displacement current that appears during charging and discharging) which is more power effective than thermally actuated devices and generates less heat. Also the method used for electrostatic actuation provides a large buckling deflection that is not yet reached when deflection to beam length ratio is considered. This can be interpreted as deflection amplification since the comb drive deflection is nearly tripled in such a nanoelectromechanical system. We electrostatically controlled the compressive stress and lateral force on a slender nanobeam, and thereby demonstrated various device operations. As a demonstration of low-dissipation ($\sim$ nW/bit) memory, one ‘bit’ of information was stored by guiding the buckling direction of the beam into either of two discrete configurations. Moreover, we showed that the beam can be used as a nano-manipulator reaching maximum displacements as large as 12% of the beam length towards each side. We performed fatigue tests and observed that the device does not show any discernible degradation even after 10,000 cycle. Controllable stiction and retraction from a nearby gate was demonstrated which shows the potential for switching applications. Further, by tuning the potential energy barrier and the degree of symmetry between two stable states, we observed noise-induced transitions between the states in a scanning electron microscope (SEM) environment presumably due to snap-through instability.[32, 42]

The device structure and operation are as follows (Figure 1.2a). The device is composed of four main components: a beam whose buckling is controlled; an inverted comb drive actuator to generate compression and initiate buckling; a modified crab leg spring[43] for recovering back to unbuckled state; and side gates for controlling buckling direction. The structural material is p-doped silicon, and the metallization layer is gold. The beam is 150 nm wide, 250 nm thick and 40 μ m long. The inverted comb drive actuator is composed of interdigitated finger electrodes, and used for axial force generation (P) on the beam to initiate buckling. The comb drive actuator[43] consists of a stationary and a mobile comb which are controlled by two DC voltages, V_{stat} and V_{mov} , respectively. The mobile part is mechanically and electrically connected to the beam. Modified crab leg design supports the structure and provides a restoring mechanism when the comb drive voltages are nulled. Side gates are placed near the beam for

generating transverse force on the beam by applying DC voltages (V_{left} and V_{right}) just before the onset of buckling to preload and guide the beam to the desired buckling direction (left / right). The buckling direction is thus controlled as shown in Fig. 1.2b,c and Video 1.

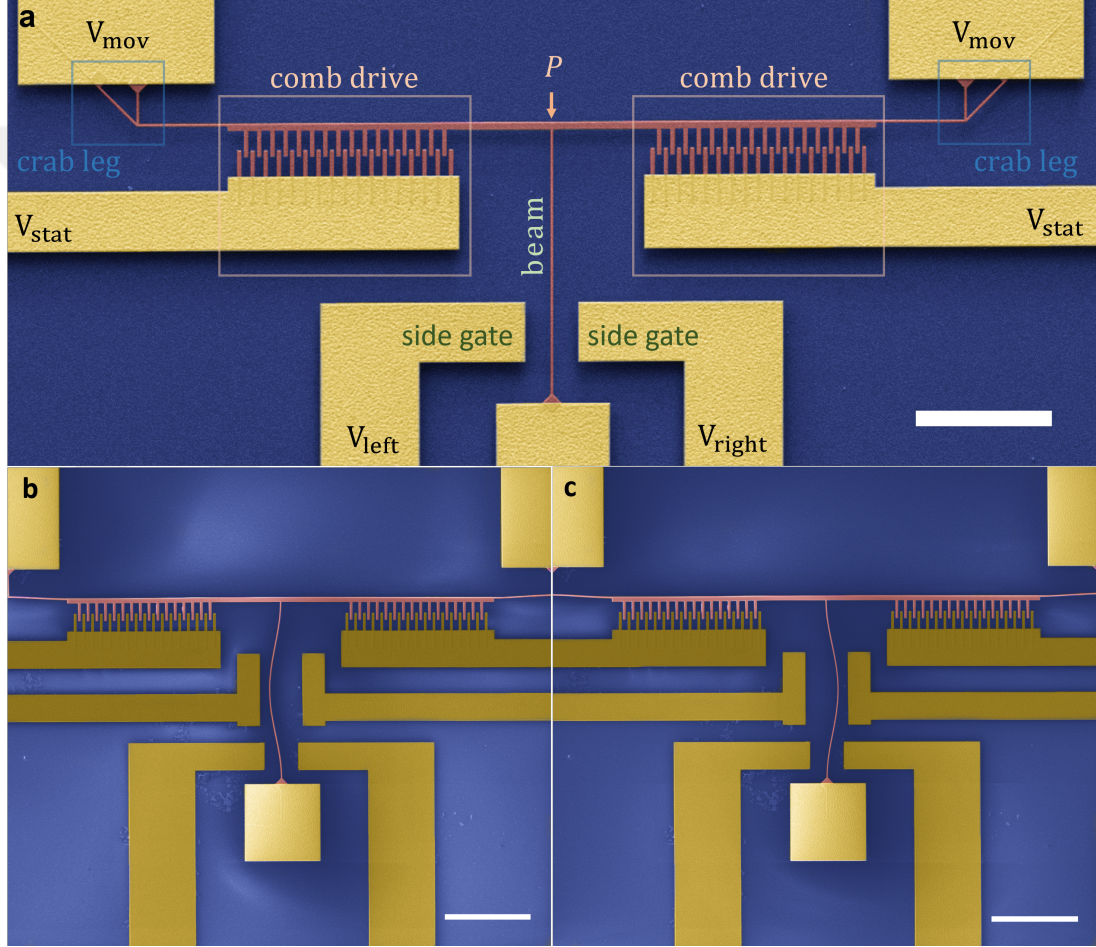


Figure 1.2: Electrostatic Control of Buckling. (a) The mechanical and electrical components of the device. Buckling is initiated on the beam through the compression force (P) generated by comb drives through the application of V_{mov} and V_{stat} . To control the direction of buckling, side gates are placed with separate control voltages V_{left} and V_{right} which are applied before buckling. By adjusting the side gate voltages, controlled buckling to the left (b) and to the right (c) can be accomplished. The devices in (b,c) are slightly different than the one shown in (a), due to the addition of extra side gates for electronic readout. Scale bars are: 20 μm .

1.1 Thesis Outline

Chapter 1 starts by presenting brief information about NEMS, recent developments in NEMS technology, their applications and advantages. Then our NEMS' applications, capabilities, features and system overview are introduced.

Chapter 2 explains micro-/nano-fabrication techniques used for fabricating the NEMS device. Firstly, a brief information is given about what micro- and nano-fabrication are. Then starting from the mask designing phase, each fabrication step used in this project is explained briefly including the working principle and how they are used through the flow of fabrication of our device. This chapter contains information about wafer/substrate cleaning, lithography, deposition, lift-off, wet and dry etching, wire-bonding and characterization processes. Finally, the fabrication flow is visually explained step by step.

Chapter 3 starts by providing brief information about NEMS transduction. Electrostatic actuation, which is used for actuating our NEMS device, is explained succinctly. Designed and fabricated electrostatic comb-drive actuator's specific dimensions and parameters and how they are determined is explained. Furthermore, static and switching power consumption due to comb-drive actuation is examined in this chapter.

In Chapter 4, applications done by using the fabricated NEMS are presented. Two experiments conducted under scanning electron microscope (SEM) and using microwave resonator coupling are explained with their test setups, procedure, and results.

Chapter 5 presents the brief summary of the work in this M.S. thesis, possible developments and changes for the future work.

Chapter 2

Fabrication Methods for NEMS

Microfabrication is a collection of techniques used to fabricate devices in the micrometer range, including integrated circuits (IC), microsensors, solar cells, MEMS and countless nanotechnology applications. Typical dimensions of the fabricated devices can range from atomic layer thickness to hundreds of micrometers [44]. For fabricating devices whose minimum feature size is sub-100 nm, *nanofabrication* techniques are used [45]. Micro-nanofabrication consists of two major methods which are top-down and bottom-up. Top-down methods rely on building layers on the substrate and removing redundant parts of the layers to attain the designed device, on the other hand bottom-up methods are done by starting with smaller entities and building them up to larger functional constructs [46]. The devices in this work are fabricated by using top-down methods.

In order to realize these fabrication methods mentioned, National Nanotechnology Research Center (UNAM) in Bilkent University, Sabancı University Nanotechnology Research and Application Center (SUNUM), and Middle East Technical University MEMS Center (METU MEMS Center) facilities were used. In following subsections, which micro-nanofabrication methods are used and how they are applied to create the devices will be explained.

2.1 Design

Micro-nanofabrication sequence of a device requires with planning and conceptual design. Each possible design concept is compared to each other in terms of feasibility, simplicity and the required layer by layer manufacturing steps. Therefore a latter step may be changed due to a former step. After a detailed feasibility study that contains the necessary fabrication processes, the fabrication flow can be generated. The first step of composing a fabrication flow is to decide what type of wafer will be used to produce the device. It is an important part of design process because the following layers will be built on that substrate. Then the layers to construct the device are drawn by using GDSII (Graphic Design System) editors such as CleWin, Elphy Plus GDSII Editor and Layout Editor.

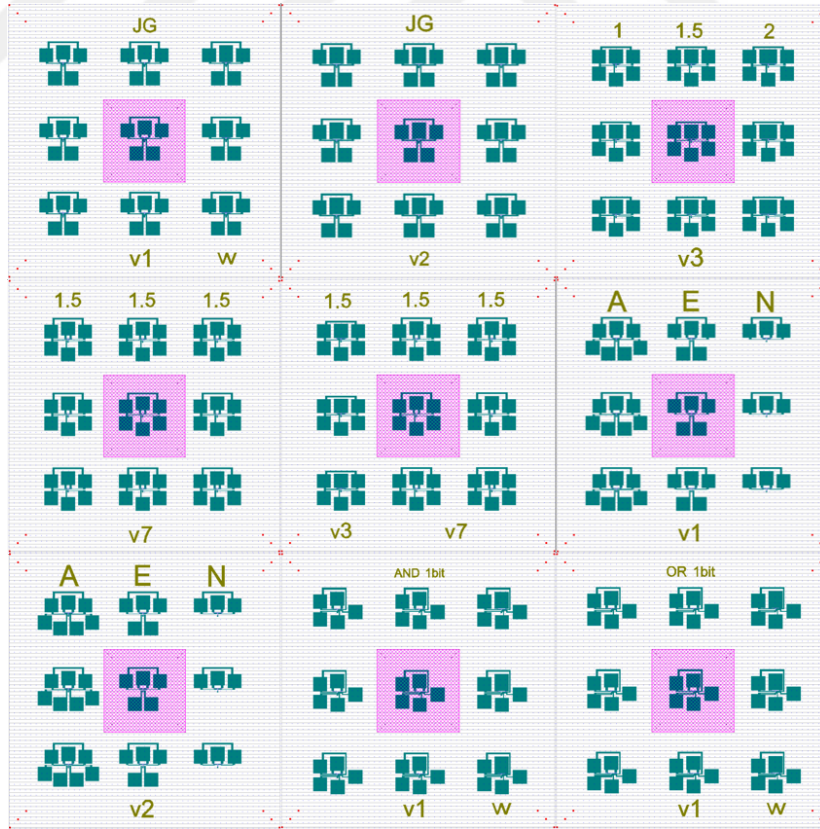


Figure 2.1: A multi-layered GDSII design for electron beam lithography. Each layer is determined with different color. Numbers and labels are used to identify the devices.

2.2 Sample Cleaning and Preparation

Contamination of the surface is an undesired situation, as the whole system is built on substrate surface. Airborne particles and dust in the environment, skin flakes and hair strands of the operators, solvent taints are the main contaminants which can be encountered. Comparing these contaminants' size and the dimensions of the device fabricated, it is seen that the contamination of the surface makes the proper fabrication impossible. In order to preclude chips fabricated from the contaminants, micro-nanofabrication processes are done in clean room where temperature, pressure, humidity and intensity of airborne particles are controlled. Clean rooms are classified depending on the average particle size per cubic foot in the environment. In order to use the clean room, users must wear the provided gowns and gears by following the procedures determined by the facility. However, following the clean room procedures and keeping substrates in clean room are not enough to prevent contamination on the surface. Wafers or samples can be reused after applying certain cleaning procedures to get rid of organic, ionic and native oxide residues on the surface. Additionally, wafers that waited without being processed for a long time need to go under these certain cleaning procedures in order to prepare a clean fabrication surface. In this work, samples are prepared for fabrication applying 2 steps RCA cleaning procedure, which was developed by Werner Kern in Radio Corporation of America in 1965 [47]. While RCA-1 is useful for getting rid of organic residues, RCA-2 is applied for cleaning ionic contamination on the surface. In addition to RCA procedure, in order to strip the native oxide layer, samples are dipped in HF solution for few seconds as a third step. If the contamination reached to visible level, piranha solution which is a mixture of sulphuric acid and hydrogen peroxide can be used as preliminary step. RCA cleaning procedure depending on [47] used in this work is demonstrated in Table 2.1.

Table 2.1: RCA Cleaning Procedure for Samples

RCA-1:

- 1 part of aqueous NH_4OH (ammonium hydroxide, 29% by weight of NH_3) added to 5 parts of DI water.
- Solution heated up to 75°C. Solution removed from hot plate.
- 1 part of aqueous H_2O_2 (hydrogen peroxide, 30%) added to solution.
- When bubbles formed (approximately in 2 minutes), soak the sample in the solution for 15 minutes.
- Rinse sample with DI water.

RCA-2:

- 1 part of aqueous HCl (hydrochloric acid, 37% by weight) added to 6 parts of DI water.
- Solution heated up to 75°C. Solution removed from hot plate.
- 1 part of aqueous H_2O_2 (hydrogen peroxide, 30%) added to solution.
- When bubbles formed (approximately in 2 minutes), soak the sample in the solution for 15 minutes.
- Rinse sample with DI water.

HF dip:

- 10 seconds BOE(1:7) dip in room temperature.
 - Rinse with DI water.
-

Even though RCA cleaning procedure is applied at the beginning of fabrication or after an incorrect or uncompleted processes, there is another cleaning procedure called basic cleaning procedure which can be applied for every steps of fabrication unless the structure is suspended or there is organic layer (photoresist etc.) on the substrate. This procedure comprises soaking and rinsing of samples with acetone, isopropyl alcohol (IPA) and deionized (DI) water, as shown in Table 2.2. In addition to the tabulated procedure, if necessary samples can be baked at 120°C to vaporize humidity. As evaporation of any of these solvents could leave residues on the surface, these steps of the procedure should be done swiftly.

Table 2.2: Basic Cleaning Procedure for Samples

Basic Cleaning Procedure:

- Soak samples in acetone bath.
 - Rinse samples with flowing acetone.
 - Soak samples in IPA bath.
 - Rinse samples with flowing IPA.
 - Rinse samples with flowing DI water.
 - Dry samples with nitrogen (N_2) gun.
-

Although for in IC industry large wafers are used for fabrication, as we use samples for research and making prototype purposes, smaller samples are cut out from a wafer with an automated diamond saw to obtain samples with same size. In this work, $2 \times 2 \text{ cm}^2$ samples were diced out of 6 inches commercially available silicon on insulator (SOI) wafer. In order to protect the wafer surface from dust while sawing, substrate is coated with thick layer of photoresist before dicing it. After dicing process is over, the samples are soaked into an acetone bath to get rid of the protective photoresist layer.

2.3 Lithography

Lithography refers for printing or patterning for a layer which will be developed on a substrate. By using lithography first commercial integrated circuits were developed in 1961 [48]. In this work even the main pattern transfer method is electron beam lithography, for larger numbers of devices constructed on a wafer, photolithography can be used as a method to pattern contact pads.

2.3.1 Spin Coating

In order to make lithography (either photolithography or electron beam lithography) samples must be coated with an organic photoresist. Among different types of coating methods such as spray coating, dip coating, plasma coating etc., spin

coating is the one used for this work. Spinning samples at very high speeds enables a uniform photoresist distribution on top of the substrate surface. After sample is prepared with certain cleaning procedures, it is baked on a hot plate at 120 °C for one minute to get rid of moisture on top of the surface. General procedure goes on with pouring photoresist on top of the surface of the substrate, then it is placed and fixed by backside vacuum on the spinner. Required thickness is calculated depending on the spinning speed curves available from the manufacturer for the specific photoresist used and the parameters such as speed and acceleration of the spinner is determined. After spin coating, the substrate is baked on a hot plate at a specific temperature. Spin coating recipes made for this work are available in Tables 2.3 and 2.4.

Table 2.3: AZ 5214 E Photoresist Coating (1.4 μm thick) Recipe

-
- Clean the chip (Acetone, IPA, DI Water, N_2).
 - Bake chip on hot plate at 120°C for 2 minutes.
 - Coat HMDS with 4000 rpm velocity 2000 rad/s acceleration for 40 seconds.
 - Coat AZ 5214E photoresist with 4000 rpm velocity 2000 rad/s acceleration for 40 seconds.
 - Bake wafer on hot plate at 110°C for 2 minutes.
 - Cool the chip with N_2 .
-

Table 2.4: Bilayer PMMA Coating (300 nm thick) Recipe

-
- Clean the chip (Acetone, IPA, DI Water, N_2).
 - Bake chip on hot plate at 180°C for 10 minutes.
 - Coat PMMA 495 A4 resist with 2000 rpm velocity 1000 rad/s acceleration for 40 seconds (~ 215 nm thick).
 - Bake chip on hot plate at 180°C for 5 minutes.
 - Coat PMMA 950 A2 resist with 3000 rpm velocity 1000 rad/s acceleration for 40 seconds (~ 85 nm thick).
 - Bake wafer on hot plate at 180°C for 10 minutes.
 - Cool the chip with N_2 .
-

2.3.2 Photolithography

Photolithography process is used to transfer pattern from a photomask to substrate coated with organic photoresist by exposing ultra violet (UV) light. Photoresists are photo-sensitive mixtures of photo-active organic polymers with solvents. When UV light is applied to the photoresists depending on its type (*positive* or *negative*), due to a chemical reaction the bonds between molecules strengthens or loosens. If the photoresist type is positive the bonds loosen, if it is negative type the bonds strengthen. In order to apply photolithography, commercially available 5x5 inches soda lime glass coated with chrome patterned photomasks are used. Photomasks depending on the type (*positive* or *negative*) prevent or allow UV light to expose the coated photoresist on the substrate.

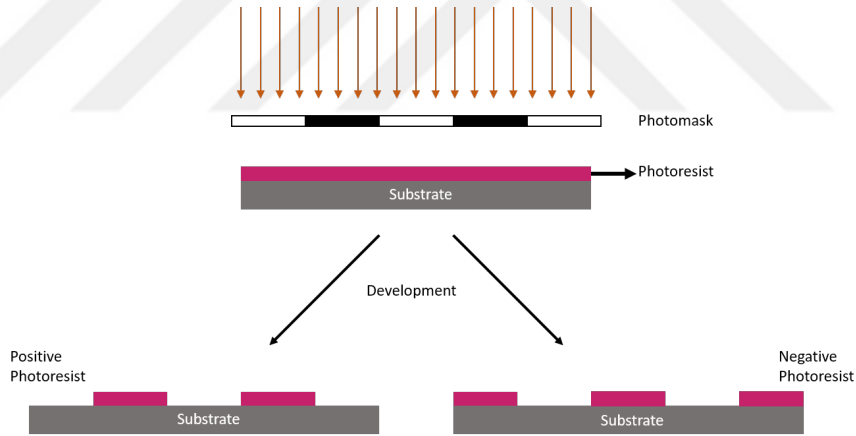


Figure 2.2: Representation of positive and negative photolithography

After the photoresist layer is exposed to UV light, sample is dipped in a chemical dissolver called *developer*. For positive photoresist, exposed parts by UV light are dissolved; whereas for negative photoresists, unexposed parts are dissolved in the developer. In order to stop the reaction between the exposed photoresist and developer, the sample is rinsed with DI water. Developed sample can be characterized under optical microscope. If photoresist is not dissolved completely (underdevelopment), development process is applied again. Additionally, if photoresist is dissolved too much or entirely (overdevelopment), for the next sample, the dipping duration should be reduced, or exposure dose should be reduced, or developer should be diluted. After development process, in order to obtain better

adhesion of resist to the substrate, sample is baked on hot plate at 110 °C for 60 seconds. The recipe for developing photoresist is shown in Table 2.5.

Table 2.5: Photoresist Development Procedure

Prepare a solution containing AZ 400 K developer : water (1:4).
Soak the sample in to the solution bath for 1 minute.
Take out the sample and clean it with water to stop reaction.
Bake sample on hot plate at 110°C for 1 minute.

In this work photolithography is not used, however if large numbers of devices will be built on a larger chip or wafer, it would be easier making photolithography by using positive photoresist for contact pads considering certain amount of time spent on fabrication.

2.3.3 Electron Beam Lithography

Comparing to photolithography, electron beam lithography (EBL) is used for higher resolutions, especially sub 100 nm, patterning. While making EBL process, there is no mask used for writing; accordingly this fabrication technique is described as direct writing. Moreover, in contradistinction to UV light, for exposure of the resist, electron beams are used. Besides, resists used for EBL are different from the photoresists used photolithograph. In Spin Coating Section, two recipes of bilayer resists used in EBL process were demonstrated. In this work, two EBL devices are used in different facilities; one of which (FEI SEM - Raith) is found in UNAM that is used for the fabrication of first 3 samples with manual alignment, then due to feasibility issues the fabrication is made by collaborating SUNUM having automatic alignment and marker detection features (Vistec/Raith). The general procedure that is followed for EBL in UNAM explained below:

SAMPLE PLACEMENT

- Sample is placed and N_2 is blew gently to sweep any dust or contaminants.
- Samples corner is scratched a little with a metal tweezer, when the sample is too smooth to focus.
- Chamber is pumped from the SEM control screen.

SAMPLE ADJUSTMENT (No Alignment Procedure)

- Start point is chosen located on the stage where chip is not placed.
- Bottom left corner of the placed sample is monitored.
- Bottom of the chip is aligned to make it parallel to screen.
- Beam voltage and beam current are set to desired values.
- Rough focus (x10k) is made then the working distance is arranged to 5 mm.
- Bottom left corner point of your sample is adjusted as the 'Origin' (0,0) on ELPHY Plus (EP).
- The same point is selected as the 1st point for angle correction then bottom right corner of your sample is selected as the 2nd point and "Angle Correction" is adjusted.
- Now the bottom left corner is origin; (X,Y) on the SEM control screen has to be matched with the (U,V) on EP screen.

SETTING THE STEP SIZE

- Rough focus on piece of dirt (x20k) is made.
- This location is saved on stage coordinates to come back to the point later.
- Z, T and R coordinates are ticked off to prevent them to change and then the stage is moved to Faraday Cage position.
- Faraday Cage is centered and zoomed in to maximum magnification.
- The current read from the "Micro Ammeter" is written.
- Desired write-field is set. Working area should be smaller than the write-field.
- On the "Calculator" in patterning tab, the current form ammeter and step size are written then the dwell time is calculated.
- Beam speed should not be higher than 11 mm/s. If so the step size is increased. If the step size is not smaller than minimum feature size of design, beam current should be lowered.

SETTING POSITION LIST AND PATTERNING

- The saved location where the dirt is located is opened again.
- At least at x75k magnification, focus is made. Focusing in higher magnification is better for patterning.
- Desired write-field is set from EP.
- Design is put to a position list.
- Desired dose and U,V coordinates are entered.
- From parameters button, the time is calculated. If the time result is unexpected, it means something is wrong.
- Before starting scanning, “drive to position” is selected and it is checked if the U,V and X,Y coordinates are matched.
- If everything is set, scanning can be started by selecting all designs put in the position list.

When the scanning (patterning) is completed, the chamber is vented out and the sample is developed with methyl isobutyl ketone (MIBK) solution as demonstrated on Table 2.6.

Table 2.6: PMMA Development Procedure

-
- Dip in MIBK:IPA (1:3) solution for 1 minute.
 - Dip in MIBK for 5 seconds.
 - Dip in IPA for 30 seconds to stop reaction.
 - Dry sample with N_2 .
-

2.4 Deposition

Deposition is simply coating a sample with required material depending on the fabrication flow by using different techniques. These techniques can be separated into three groups: physical vapor deposition (PVD), chemical vapor deposition (CVD) and liquid phase deposition (LPD). LPD is the method used for coating liquid materials such as photoresists by using spin coating, sol-gel, and electro-chemical techniques. CVD methods are used for deposition of source materials in gas phase to a sample surface. The source gas flows near the heated substrate, while flowing, the molecules decompose and react with the substrate surface. During the reaction, a film grows on the surface, thus the surface is coated. Moreover, gaseous by-products composed during the reaction are pumped away. On the other hand, for PVD, target material is in solid phase and by heating its physical state is changed to coat the sample surface. PVD is the most valid method for metallic thin film deposition, besides, some semiconductors and oxides can be deposited. PVD method contains thermal evaporation, electron beam (e-beam) evaporation, sputtering, molecular beam epitaxy and so on. From all these deposition methods, in this work, spin coating (for resist coating), thermal evaporation and e-beam evaporation are used.

Both thermal and e-beam evaporation require high vacuum using vacuum chambers in order to create a direct linear pathway for atoms to reach the substrate surface and prevent them from colliding with each other. Besides in insufficient vacuum, even if target atoms may reach to the surface without collision, the deposited layer would be unqualified due to the particles in chamber atmosphere sticking to the surface. Thus, the pressure of the vacuum chamber should be at levels ($\sim 10^{-6}$ Torr [44]) of that the mean free path of the evaporated molecules is larger than the distance between the target material and the substrate surface.

Before starting the deposition of a material, material density, acoustic impedance and tooling factor values are set as inputs. In order to conduct a fine deposition the calibration the quartz crystal used as a sensor should be done precisely. As the quartz crystal is also coated with the target material during the

deposition, the thickness of the deposition can be tracked by the change of the resonance frequency (due to the added weight) of the crystal and monitored from the thickness monitor. In addition to this, the velocity (rate) of the deposition can be monitored from the rate monitor. After multiple evaporation processes, the crystal should be changed because its sensitivity decreases.

During evaporation process, as the molecules of the heated target material to its melting point reach to the substrate surface, the substrate's temperature increases. When the vacuum of the chamber is brought to the atmosphere conditions right after the process is over, due to the rapid cooling of the surface, there would be thermal stress which cause the coated film to buckle. For this reason, the coated sample is left to rest for 15-20 minutes without breaking the vacuum of the chamber.

2.4.1 Thermal Evaporation

Thermal evaporation is a deposition method to coat (mostly thin metallic) film onto the substrate surface by using DC electric current to heat the target material to its melting point temperature. For evaporation, a target material is placed in metallic (Molybdenum (Mo), Tungsten (W), etc.) boats. While high current (around 100-150 A) is passing through the thermal boat, the heated target material evaporates. By thermal evaporation, target materials with melting point up to 1800 °C can be coated. During thermal evaporation process, the current passing through the boat should not be changed fast because it may cause failure of the boat and thus, the process is shut down. Additionally, fast changes of current end up with non-uniform film deposition to the substrate surface as the rate changes fast too.

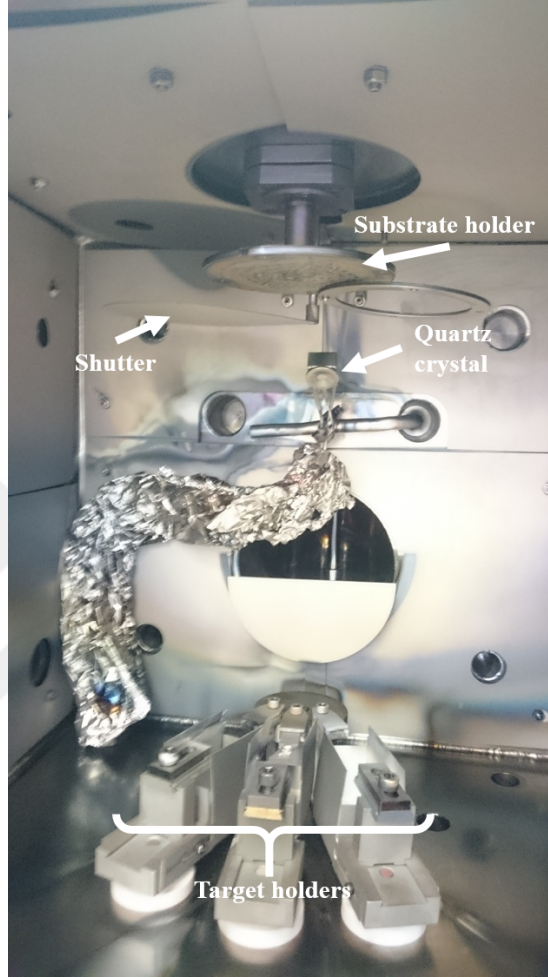


Figure 2.3: Thermal evaporator chamber which has 3 target holders enabling for coating 3 different materials simultaneously.

In this work, thermal evaporation is used to make deposition of gold (Au) contact pads. In order to coat Au on top of silicone substrate, an adhesive layer is required which is 4-5 nm chrome (Cr) layer for this case. The Cr layer is coated with small rate such as 0.3-0.4 Å/s; then the Au layer is coated with 0.5-0.8 Å/s rate until it becomes ~100 nm. When the deposition process is over, the substrate is left in the vacuum to rest for 15 minutes.

2.4.2 Electron Beam Evaporation

Target materials whose melting point temperature is higher than 1800°C cannot be evaporated by thermal evaporator, for those materials electron beam (e-beam) evaporator is used. A stream of high energy electrons directed magnetically excites the target material [49]. In e-beam evaporator, target materials are put in crucible which is placed in water cooled hearth that protects it from harm of high temperatures. In this work, e-beam evaporator is used for SiO_2 mask deposition. When the deposition process is over, the substrate is left in the vacuum to rest for 15 minutes.

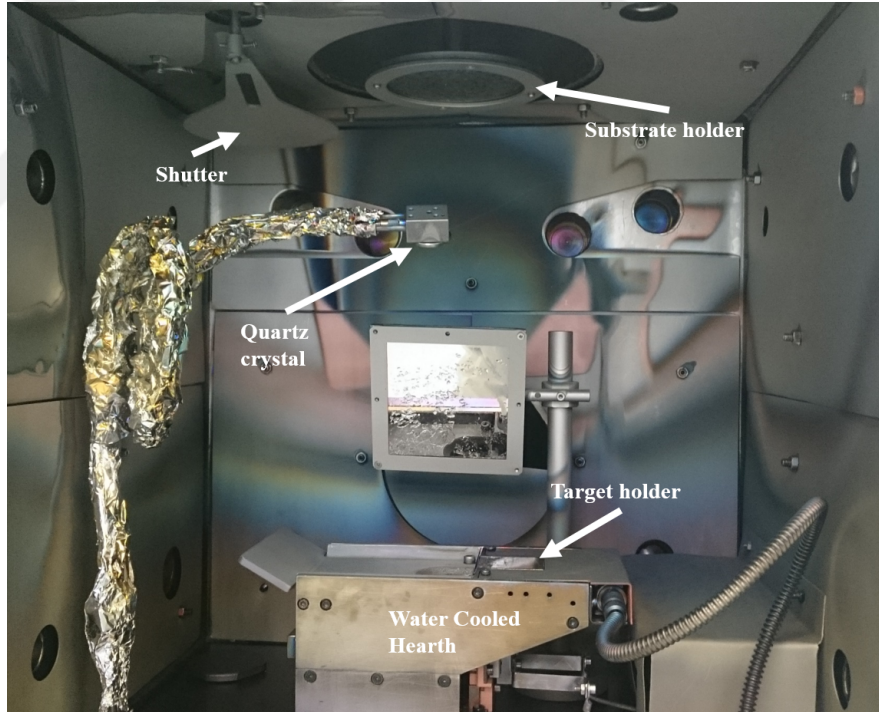


Figure 2.4: Electron beam evaporator chamber whose crucibles (target holders) are put in the water cooled hearth and the deposition process is monitored by the mirror showing the selected crucible.

2.5 Lift-Off Process

After the deposition of a material is completed on a patterned resist surface made by lithography, the sample is left into an acetone bath to get rid of resist under the deposited material for at least 8 hours depending on the minimum feature size. This process is named as lift-off which is demonstrated in Fig. 2.5. The acetone bath should be sealed (in our study by aluminum foil) so the acetone cannot evaporate. The ratio between the coated resist in lithography and deposited material thickness should be 3:1 for a successful lift-off. Otherwise, the side-walls of the resist would be coated with the target material which causes a lift-off problem.

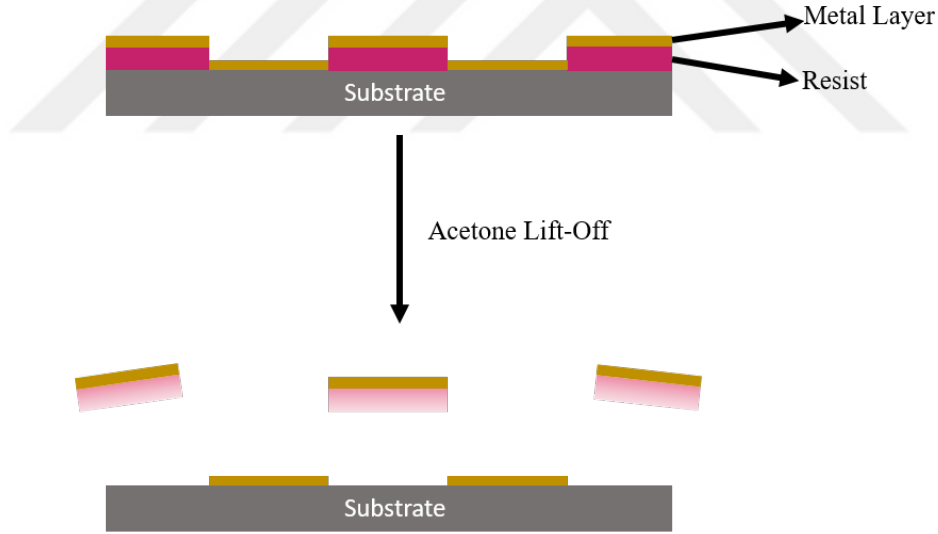


Figure 2.5: Representation of Lift-off Procedure

For this work, overnight lift-off process is used for the structures with minimum feature size of 150 nm. After the lift-off process, the sample is stirred in sonic bath for 2 minutes. If sonic bath is underdone (overdone), the small regions cannot be stripped away (the structure/mask deposited can be broken).

2.6 Etching

Etching is the removal of the materials or substrate, which is not preserved by an etch mask, physically or/and chemically. A sample can be etched after a lithography process by using the resist as an etch mask, or a thin layer of metallic or oxide layer is deposited as etch mask before etching. Etching can be examined in two subheading which are wet etching and dry etching.

2.6.1 Wet Etching

In order to make wet etching process, operator dips a sample into a chemical (acidic or basic) solution which is called as *etchant* reacting with the substrate surface. Etch rate is determined considering the removal rate of the etched material which is controlled with the temperature of the reaction. Moreover, etching time is critical for the desired etching amount of the material, particularly for sub-1 μm etching.

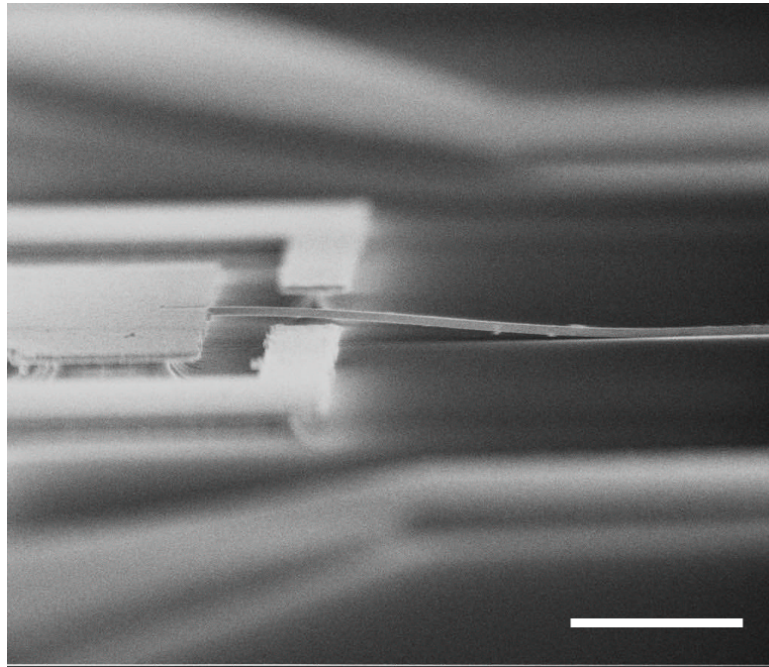


Figure 2.6: Stiction of a Si beam after BOE(1:7) wet etch. Scale bar is 5 μm .

Wet etching can cause stiction of the suspended structures to the substrate surface as shown in Fig. 2.6. The stiction occurs due to the meniscus of the drying liquid under the suspended structures. During the liquid has evaporated, there is capillary force that pulls the structure to the surface of the substrate until it completely dries [50]. When the structure contacts with the surface, because Van der Waals forces are very affective at small scale, it may remain stuck. In order to recover the stiction, critical point drier (CPD) can be used. Moreover, to remove the stiction possibility, vapor forms of those etchants can be used.

In this work, for the first three fabricated samples, successive 15 minutes ($2\text{ }\mu\text{m}$ etch) of hydrofluoric acid (HF) isotropic wet etch of silicon dioxide (BOX layer and mask) and critical point drying were made. But, due to the dirt remaining on the surface after CPD process, failure of some suspended structures, and unpreventable stiction of some structures; rest of the samples' BOX layer and SiO_2 masks are etched isotropically by HF vapor with the recipe provided in Table 2.7 is used.

Table 2.7: HF Vapor Etch recipe developed for isotropic oxide etching with 1300 Å/min rate

Recipe	Isotropic SiO_2
Stabilization Flow (sscm)	880 N_2 , 325 EtOH
Etchant Flow (sscm)	880 N_2 , 325 EtOH , 720 HF
Coil Power (Watt)	600
Platen Power (Watt)	50
Pressure (mTorr)	5
Temperature (C)	20

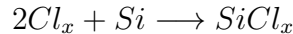
2.6.2 Dry Etching

Dry etching is used to remove solid surface or layers by using gaseous etchants. Because the etchant is gaseous, the stiction problem observed in wet etching is eliminated. Also, whereas wet etchants may not diffuse in every sub-micron gap, dry etchants can diffuse thanks to free moving gaseous molecules. In contrast with the chemical wet etching, dry etching can be physical (ion milling), chemical and

both physical and chemical (reactive ion etching (RIE)) [48]. For physical dry etching, inert (nonreactive) gases, especially Argon (Ar), are used to subtract the any material on the substrate surface by dislocating the atoms. For chemical etching, the ionized gas molecules react with the atoms on the substrate surface and the compounds are pumped away.

The gas or vapor plasma in the dry etching is created by an electric field utilized by DC, AC (+50 kHz), RF (13.56-27 MHz), or microwave fields (+300 MHz) [48]. When the free electrons in applied electric field oscillate and collide with the gas molecules in the chamber, a quasi-neutral plasma, which has equal number of positive and negative charges, is formed [51].

In inductively coupled plasma (ICP), a coil operating at 13.56 MHz drives the plasma inductively. In the upper part of the chamber where RF source is found, high density, low energy, low pressure plasma is created by coupling of ion-producing electrons through a magnetic field. In the lower part, RF bias controls the ion bombardment energy [48]. In this work, ICP device, found in UNAM, is used to etch 250 nm silicon surface anisotropically by using Cl_2 gas (because chlorine and fluoride radicals are effective to etch Si). The chemistry of the reaction is as follows [48]:



For dry etching process, the selectivity between the mask and etched layer/surface is an important criterion which also determines the deposited mask thickness. Selectivity is the ratios of etch rate between the target layer/surface between the mask layer. For etching, in order to use thin layer of mask, higher selectivity is desired. Thus, in our work, SiO_2 is used as mask considering the high selectivity between Si and SiO_2 . Moreover, it was observed that Cl_2 plasma has ability to etch gold (Au) contacts even though Au is an inert element; therefore, the thickness of deposited Au is determined considering the selectivity between Si and Au.

Thus, the recipe shown in Table 2.8 to etch silicon anisotropically was developed conceiving these criteria and characterizations during the etch tests.

Table 2.8: Etch recipe developed for 250 nm anisotropic silicon etching for STS ICP

Recipe	Anisotropic <i>Si</i>
Etchant Flow (sscm)	30 Cl_2
Coil Power (Watt)	600
Platen Power (Watt)	50
Pressure (mTorr)	5
Temperature (C)	20
Duration (Min:Sec)	2:45

2.7 Wire Bonding

For most of the fabrication flows fabrication is the final step used to connect the NEMS with the printed circuit board (PCB) which chip is mounted on. Contact pads ($200 \times 200 \mu\text{m}$) fabricated for the connection of the device are too small for soldering, thus bonding of $25\text{-}30 \mu\text{m}$ wires is inevitable. There are two types of wire bonding: ball bonding and wedge bonding. For ball bonding, first a ball is formed at the ceramic tip of the wire-bonder pad by sparking the tail of a wire, then by observing through an optical microscope the ball is bonded to the contact pad. The stage is moved slowly without harming the wire to the other pad (generally pad on the PCB) which is interested to be connected with the contact pad. At this point, wedge bonding is made by simply pressing the wire into the pad. In wedge bonding, the tip of the wire is pressed to the surface with vibration. Parameters of the process such as tip force, contact time are entered as inputs before the operation and changes depending on the surfaces which is bonded on. In this work, the wire bonding process is made at METU MEMS Center with wedge-wedge bonding.

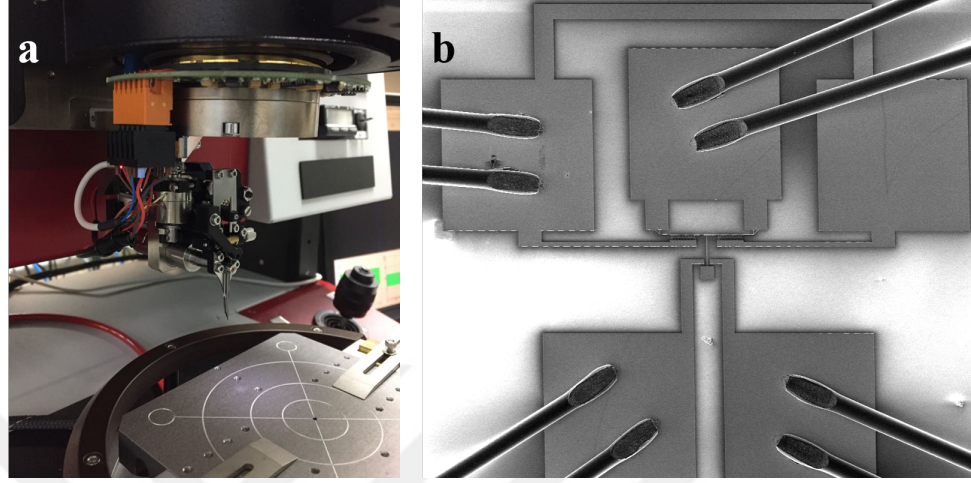


Figure 2.7: (a) Wirebond machine used in METU MEMS Center. (b) SEM image of wedge bonded device by the machine in (a).

2.8 Characterization

Characterization can be considered as the quality control and check of the fabricated device. Particularly, it gains more importance while developing a recipe for a fabrication step such as etching, lithography and deposition. Characterization of a sample can be done to learn information about thickness, topography, electrical and chemical properties. There are different methods to characterize of different properties of a sample such as microscopy (optical, scanning electron, transmission electron, etc.), spectroscopy (XRD, XPS, etc.), profilometry (stylus, optical), probing, etc. In this work, optical and/or scanning electron microscopy and stylus profilometry are used frequently in order to measure/check deposition and etch thickness of the samples.

2.8.1 Microscopy

Optical microscopy is the simplest microscopy to characterize the process done. It provides rough check of the sample with the resolution at micrometers range because the available magnification of $\times 10^4$ at maximum. In this work, after lift-off processes and dry etching process the critical parts of the structure (fingers

and gap between fingers) and the substrate surface are checked by the optical microscopy.

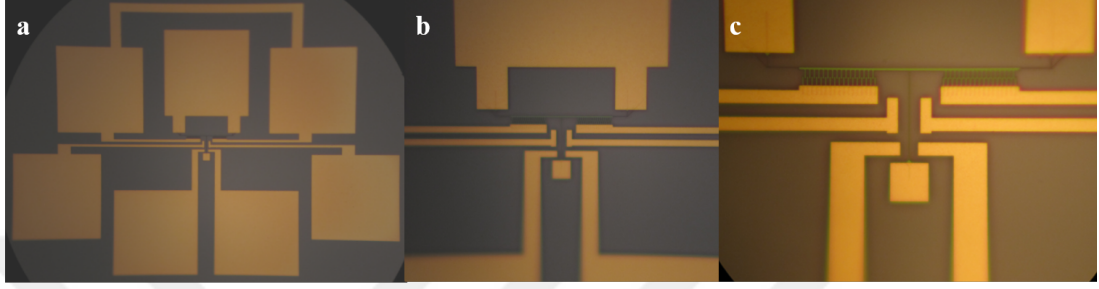


Figure 2.8: Optical microscopy characterization of a device after ICP process. Default magnification is 10x for the optical microscope in UNAM. Lens magnification is 10x for (a), 20x for (b) and 50x for (c).

Scanning electron microscopy (SEM) is used for much more detailed characterization of the sample dimensions as instead of diffraction of the light, scattering electron beams are used to create the image. Thus, the resolution of the SEM is in nanometers range. It gives opportunity to operator to check the dimensions of the structures in tilted and cross-sectional view. In contrast with the optical microscopy, to do SEM, the sample has to be placed in vacuum chamber at near 10^{-4} bar and lower. Also the surface observed has to be conductive, otherwise it should be coated with a thin layer of conductive material such as gold or platinum. For this work, SEM is used to measure the dimensions of the structure in both top view (for width) and tilted view (for cross-section).

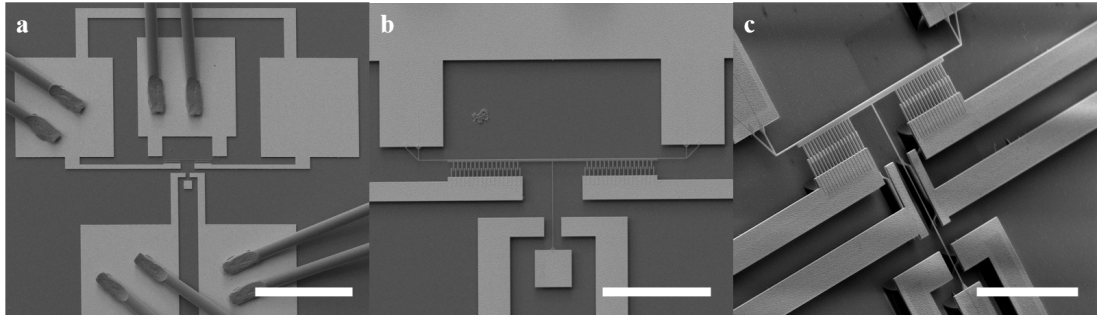


Figure 2.9: SEM characterization of a device when fabrication is completed. Scale bars are: 200 μm for (a), 50 μm for (b) and 20 μm for (c).

2.8.2 Profilometry

Profilometry is used to identify the topography of the surface. Thickness measurement of a deposited layer is reached by either physical (stylus) or optical profilometry. Whereas optical profilometry uses light to get data depending on the refractive index difference of two layers, stylus profilometry works like an atomic force microscope (AFM) with low resolution. The metallic tip of the device sweeps by contacting on the surface and measures the elevation difference between two layers. There is a drawback of stylus profilometry which is that it is not suitable to use on soft surface as the tip scribes the coated layer. In this work, stylus profilometry is used to thickness data both after deposition steps and dry etching of the silicon device layer.

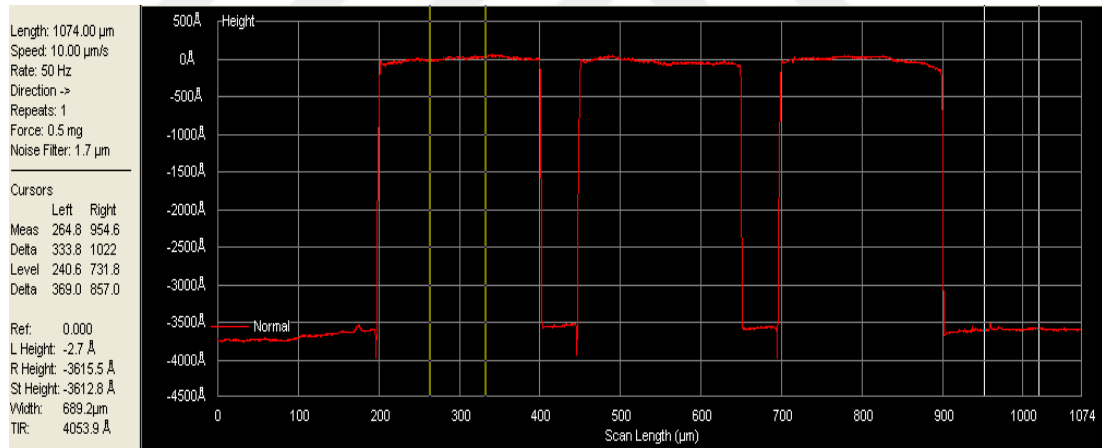
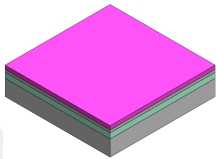
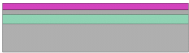
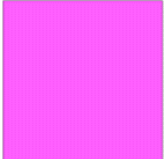
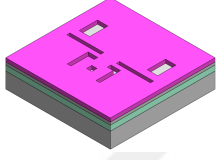
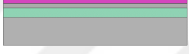
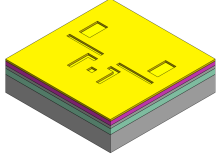
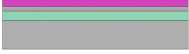
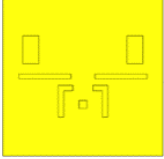
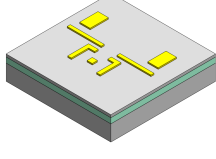
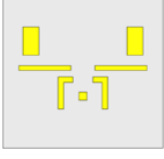
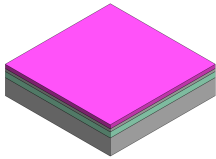
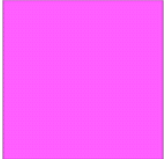
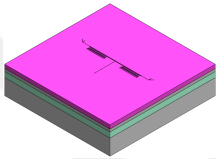
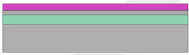
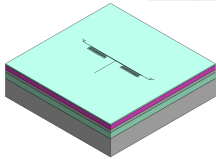
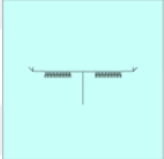
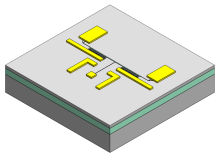
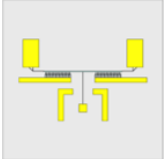
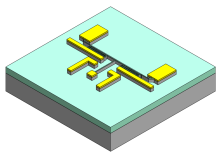
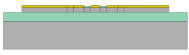
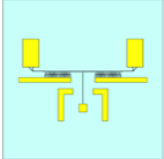
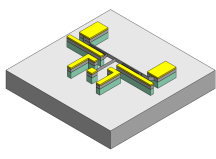
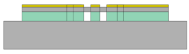
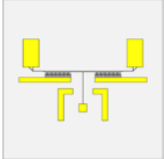


Figure 2.10: An example stylus profilometry result from a fabricated device after ICP.

2.9 Fabrication of the Device

Isometric View	Side View	Top View	Process Step
			300 nm bilayer PMMA resist is coated on SOI chip with 250 nm silicon (Si) device layer and 3 μm buried oxide (BOX) layer.
			By electron beam (e-beam) lithography, contact pads and alignment markers are patterned on the SOI chip.
			~ 120 nm gold (Au) is deposited on the surface of the substrate using thermal evaporator.
			After an overnight lift-off process, unpatterned regions are stripped away.
 Si	 SiO ₂	 Au	 PMMA

			300 nm bilayer PMMA resist is coated on SOI chip for making the second e-beam lithography.
			E-beam lithography of the second layer is made to pattern the device (the beam and the comb-drive).
			~100 nm silicon-dioxide (SiO_2) is deposited on the substrate surface by e-beam evaporator.
			After an overnight lift-off process, masked beam and comb-drive device remains on the substrate.
			Unmasked parts of top Si layer is etched anisotropically using chlorine (Cl_2) plasma by Inductively Coupled Plasma (ICP).
			Both the BOX layer and the SiO_2 mask are etched by hydrofluoric acid (HF) vapor.
 Si	 SiO_2	 Au	 PMMA

Chapter 3

Electrostatic Comb-Drive Actuation for NEMS

Actuation and sensing are gathered under the heading of *transduction*. It is simply defined as transmitting energy received from a system to another system; mostly the form of the energy changes. In NEMS, energy coming from an electronic transducer (actuator) motivates the device mechanically, then the response of the device is transduced to read out system electronically [52]. The commonly used transduction techniques for NEMS are electrostatic (capacitive), electrothermal, piezoresistive, piezoelectric and magnetomotive transductions. In this work, in order to actuate our NEMS device electrostatic actuation has been used.

Electrostatic (capacitive) force develops between two parallel plates of a capacitor when they are charged. One of the plates moves through the direction of electrical field between them, thus an electrostatic actuator is able to stretch or compress a beam. Among electrostatic actuator types, comb-drive actuator has been used in this work because of their high movement range[43, 53, 54] and low actuation voltage[55]. With electrostatically actuating comb-drive, compressive force applied to the beam to perform buckling motion is procured as shown in Fig. 1.1. Comb-drive actuator consists of two main parts: moving comb and stationary comb (stator)[43]. The electrostatic force (F_C) between these parts is

calculated as shown in Eq. 3.1.

$$F_C = \frac{1}{2} \frac{\partial C}{\partial x} V^2 = \frac{N \epsilon_0 t}{g} V^2 \quad (3.1)$$

where N , ϵ_0 , t , V and g correspond to number of fingers, permittivity constant, thickness of a finger applied potential difference and gap distance between the fingers, respectively. Here, the drive voltage to apply the critical electrostatic force is calculated by the Eqn. 3.1 and it is considered that the critical voltage value coincides with the applicable voltage range that is limited by the DC power supply.

The important parameter for initializing the buckling is the critical compressive force (P_C) acting on the beam which all the design and actuation parameters are based on. In order to trigger the buckling, F_C must be larger than P_C shown in Eqn. 3.2.

$$P_C = \frac{4\pi^2 EI}{L^2} \quad (3.2)$$

In Eqn. 3.2, E , I and L represent Young's Modulus, geometric moment of inertia and length of the beam respectively. The critical buckling force (P_C) is found approximately 290 nN, by taking Young's Modulus 167.5 GPa, by Euler-Bernoulli beam theory (Appendix A). With respect to the force calculations demonstrated in Eqn. 3.1 and 3.2, comb fingers are designed to be 4 μm long and 500 nm wide with 250 nm out-of-plane thickness while the gap distance between fingers are set to 500 nm. At the default state, finger tips are overlapping to each other by 1 μm which provides a proper actuation distance. In the stationary half of the comb-drive there are 17 pairs of fingers while the upper behalf there are 16 pairs of fingers located. The SEM images of the comb-drive fabricated with these specific dimensions and parameters is demonstrated in Fig. 3.1.

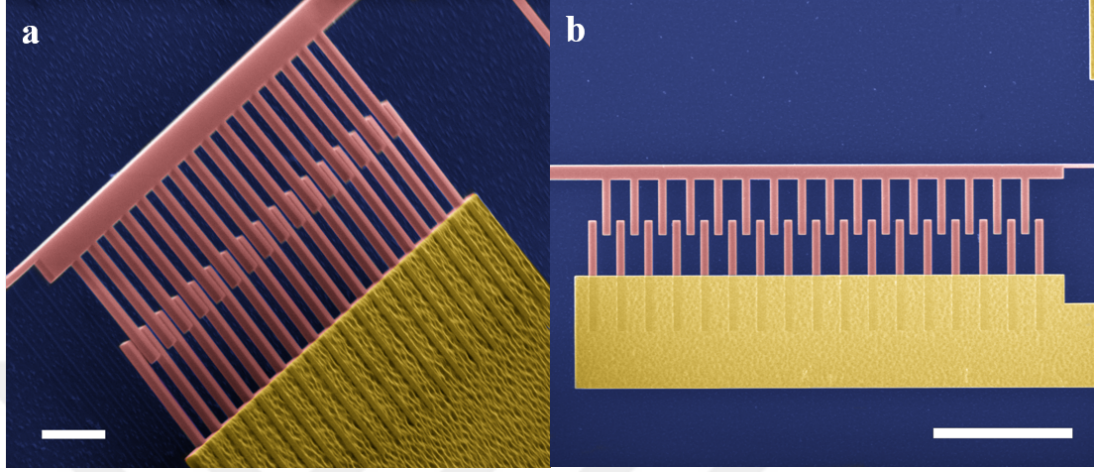


Figure 3.1: SEM Images of Fabricated Comb-drive

In order to recover buckling, the crab-leg flexure (Fig. 3.2) was designed as the springs of the comb-drive actuator considering the yield and fracture conditions of the structure. The dimensions of the crab-leg springs are determined based on Eq. 3.3[43].

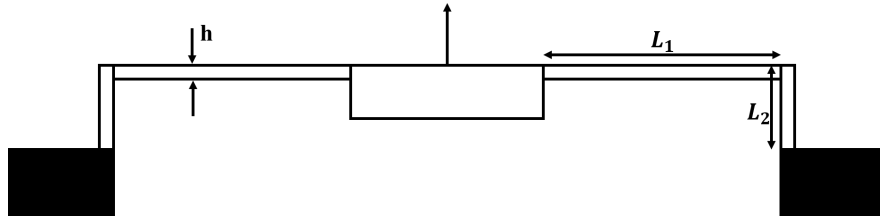


Figure 3.2: Crab-leg Spring Schematic

$$k = \frac{24EI_1}{L_1^3} \frac{L_1I_2 + L_2I_1}{L_1I_2 + 4L_2I_1} \quad (3.3)$$

where E is Young's Modulus, $L_{1,2}$ are lengths of crab-leg spring, $I_{1,2}$ are geometric moment of inertias of the crab-leg spring and k is the spring constant. With respect to this, the thickness is 200 nm, the width is 250 nm due to device layer constraint, L_1 is 13.5 μm and L_2 is 5 μm . After the experiments were done with first batch of chips, it was observed that in order to provide extra bending stiffness a pair of crosswise supporting beams with 45° are added to the design as

shown in Fig. 3.3 which prevent out-of-plane deflection of the suspended structure towards the substrate. It also prevents the vertical beam (having length L_2) of the crab-leg structure to deflect when the actuation force is applied since the bending stiffness of the vertical beam is much lower than the axial stiffness of the crosswise support beam.

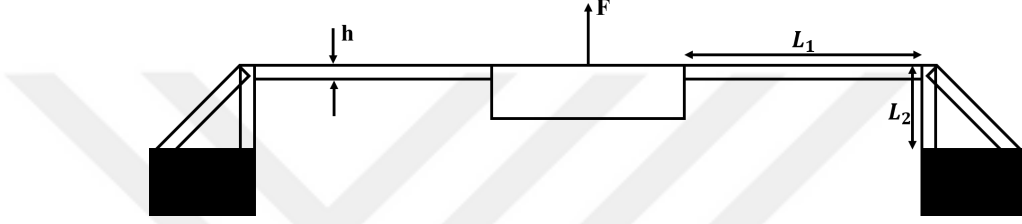


Figure 3.3: Modified Crab-leg Spring Schematic

Power Consumption in Nanobuckling

We distinguish between two types of power consumption: static and switching. Static consumption is the power required to keep the value of the bit. Switching consumption is defined as energy lost for each change of the memory state ($0 \rightarrow 1$, or $1 \rightarrow 0$ which is discussed in detail in Chapter 4).

To estimate and measure the static power consumption, we observe that the dominant contribution originates from the leakage current of comb drive electrodes which are biased with large voltages. By considering the thickness, area and resistivity of the insulating SiO_2 layer, we calculate a resistance on the order of $10^{12} \Omega$. A resistance measurement with a source unit indicated a value larger than $G\Omega$. Therefore, Joule heating formula results in a static power consumption of 0.25 nW per bit. To measure the static power consumption, we used a source unit to apply voltages on the comb electrodes and measure the resulting leakage current. When 21 V (the maximum range of the instrument) is applied to the comb gates, a power level of 0.4 ± 0.1 nW was measured. Considering that the total voltage difference is at maximum 48 V, the static power consumption is expected to be 0.9 ± 0.2 nW. Clearly, the consumption can be further reduced by

using a thicker SiO_2 layer to decrease the leakage current.

The capacitance of the comb-drive is calculated by the following equation:

$$C = \frac{2N\epsilon_0t(y + t_0)}{g} \quad (3.4)$$

where n is the number of fingers, ϵ_0 is the dielectric constant of vacuum, t is the thickness of the comb fingers, y_0 is the initial overlap between moving and static fingers, y is the displacement of the moving comb and g is the gap spacing between the moving and static fingers. To estimate the switching power consumption, we observe that charging/discharging a capacitive gate consumes a power of $\frac{1}{2}CV^2$ which is independent of the resistance. The capacitance between the two sides of the comb drive is ~ 700 aF and this results in an energy loss of 35 fJ/switch.

Chapter 4

Nanomechanical Buckling Applications

The device operation was observed with an SEM system equipped with electrical feedthroughs to apply DC voltages to the two comb drives and the side gate electrodes. A custom-designed control panel was used to handle and measure the supply and control voltages, and was additionally equipped with a programmable microcontroller circuit so that desired voltage waveforms can be applied accurately on the device (Chapter 4.1). The control of the device was accomplished entirely using DC voltages to generate electrostatic fields only. This is in contrast with thermally induced buckling[21, 41] which increases the temperature of the device by tens, in some cases hundreds, of Kelvins and consumes a large power. The static power consumption of our device is determined at the level of parasitic leakage between the silicon device layer and the substrate which are separated by a 3 μm thick oxide (we estimated and measured a static power consumption of ~ 1 nW per bit, Chapter 3). Moreover, our approach simplifies the instrumentation requirements for nanomechanical computation since previous approaches based on nanoresonators for memory storage[20] and logic gate operations[23, 24] necessitate the use of function generators which are more complex, expensive and difficult to miniaturize compared to DC voltage sources.

4.1 SEM Test Setup and Experiment

After fabrication is done, the chip containing 9 devices is placed on a specially designed PCB - with SMA ports - by using double sided copper tape. In order to achieve actuation and reading, SMA connection ports soldered to the PCB must be connected to the device. Between bonding pads on the device and copper lanes on the PCB, wires are bonded by using wire-bonder.

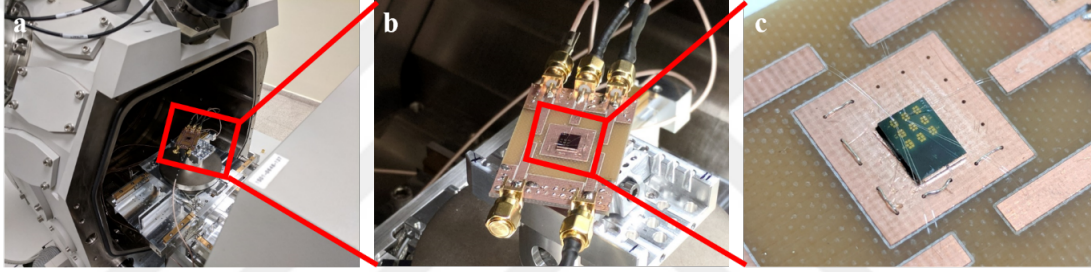


Figure 4.1: Demonstration of how the PCB which the chip is mounted on is loaded to the SEM vacuum chamber in order to use the feedthrough system

The preassembled PCB containing the chip is loaded to the scanning electron microscope (SEM) chamber for imaging the system reaction under actuation. System cables are attached to the PCB in order to achieve actuation and readout. For creating the potential difference, a regular power supply with 3 adjustable channels which can supply 31.8 V each. Between power supply and device PCB, specially designed control panel which controls the on/off states of supply voltages is used. Control panel consists of on/off switches, resistances, indicator LEDs and BNC connections in the output and input ports. Moreover, control panel has a common ground connection through its chassis that connects all ground cables together.

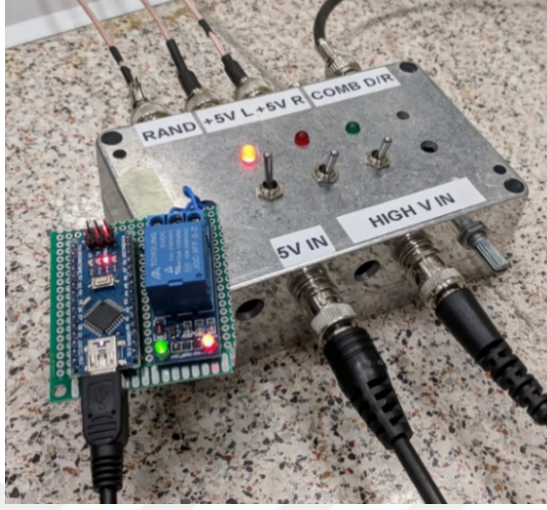


Figure 4.2: Control panel used for controlling DC voltages applied through the feedthrough system

At the outset, stationary combs are loaded with $+30\text{ V}$ and one guidance probe is activated through the control panel. After setting the movable comb supply voltage to -15 V — according to the critical force calculations in the comb-drive structure — combs are loaded by turning the control switch on.

Two different test strategies are used to observe two different outcomes of the device. First consideration is achieving the binary logic operation by observation of left and right buckling in consequent actuation processes. To test this behavior, while stationary combs are loaded with $+30\text{ V}$, firstly left guidance probe is activated and pre-set movable comb voltage is given to the system by turning on the related switch. After left buckling is observed, both guidance and movable comb drive switches are deactivated. For the opposite buckling observation, right guidance probe is activated from the control panel and the same pre-set driving voltage is applied to the movable combs. This process is repeated for several times in order to test the consistency of the control system. An embedded microcontroller (Arduino Nano) is used to regulate and automatize the operation of the device in a repeatable and controllable manner.

Second process aims to test the controllability of the lateral buckling displacement by fine tuning of the driving voltage. First step is same as the general procedure; stationary combs are loaded with +30 V. An arbitrary guidance probe is activated from the control panel and this time movable comb drive voltage is set to -10 V. After activating the movable comb drive voltage, potential is increased – which eventually generates a higher vertical force – from the power supply in a controlled manner and related beam deflection is observed in the SEM imaging system.

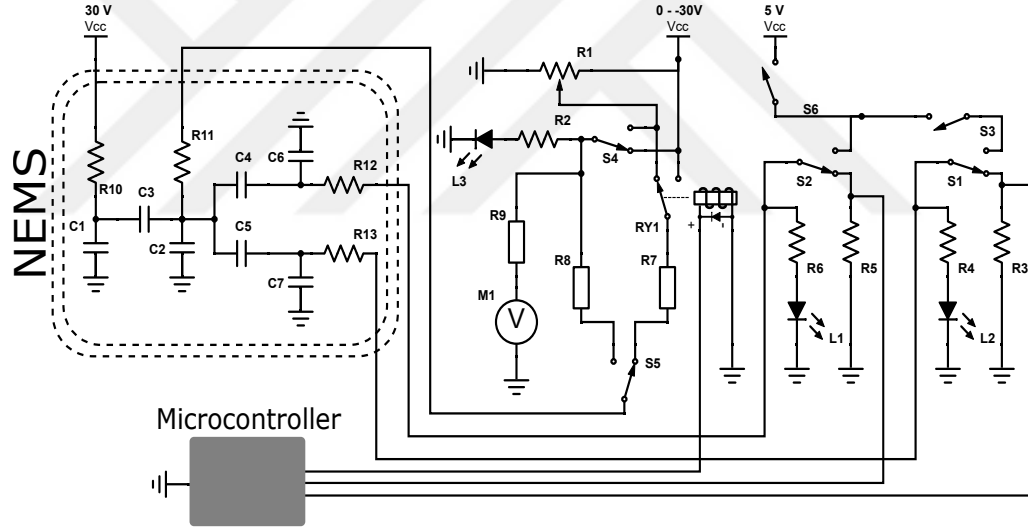


Figure 4.3: Circuit demonstration of NEMS, Control Panel and microcontroller during experiment under SEM.

Throughout the process, LED indicators on the control panel ensure that desired loading is achieved and for measuring the voltage level of the movable comb, a multimeter is connected to the control panel's mutual drive/readout port. From the beginning of the process, all reactions of the device are recorded by the SEM and snapshots are taken at specific moments which comprises important data about deflection for the post processing.

After every test session, drive voltages are cut in the reverse order that is applied in the loading phase. At the end of all measurements, all power sources are deactivated, PCB is removed and all connections are detached.

4.2 Buckling Under Scanning Electron Microscope

We performed experiments to test the suitability of the beam buckling characteristics for storing information. The protocol for storing information consists of three steps: preload, write and retain (Fig. 4.4a and Video 3). In the **preload** stage, the information to be stored is provided by the side gate electrodes. To write logic 0, the left side gate is activated by applying 5 V; similarly, logic 1 is written by applying 5 V to the right side gate. At this point, the beam still remains at the unbuckled state. During the **write** stage, the comb drive is actuated to initiate the buckling on the beam, while the side gate voltage is still kept active. Owing to the force generated by the activated side gate, the symmetry of the system is broken and the buckling direction will be towards the activated side gate (left or right). The side gate voltage used during the **write** process affects the displacement after buckling only slightly, but determines the buckling direction unambiguously and systematically. In the absence of a control voltage, even the slightest asymmetry in the electrostatic pull of the side gates can bias the buckling direction unpredictably and perform a spurious **write** operation as the system encounters the pitchfork bifurcation.[56] A finite control voltage therefore biases the buckling in a unique direction, so that the influence of the gate attraction is no longer critical. After the write step, the **retain** step begins where the side gate voltage is brought back to zero, therefore the signal representing the original information is removed. Although the beam pulls back slightly, it nonetheless remains deflected in the same direction. Thus, the logic state is transferred from the data line to the beam and stored permanently.

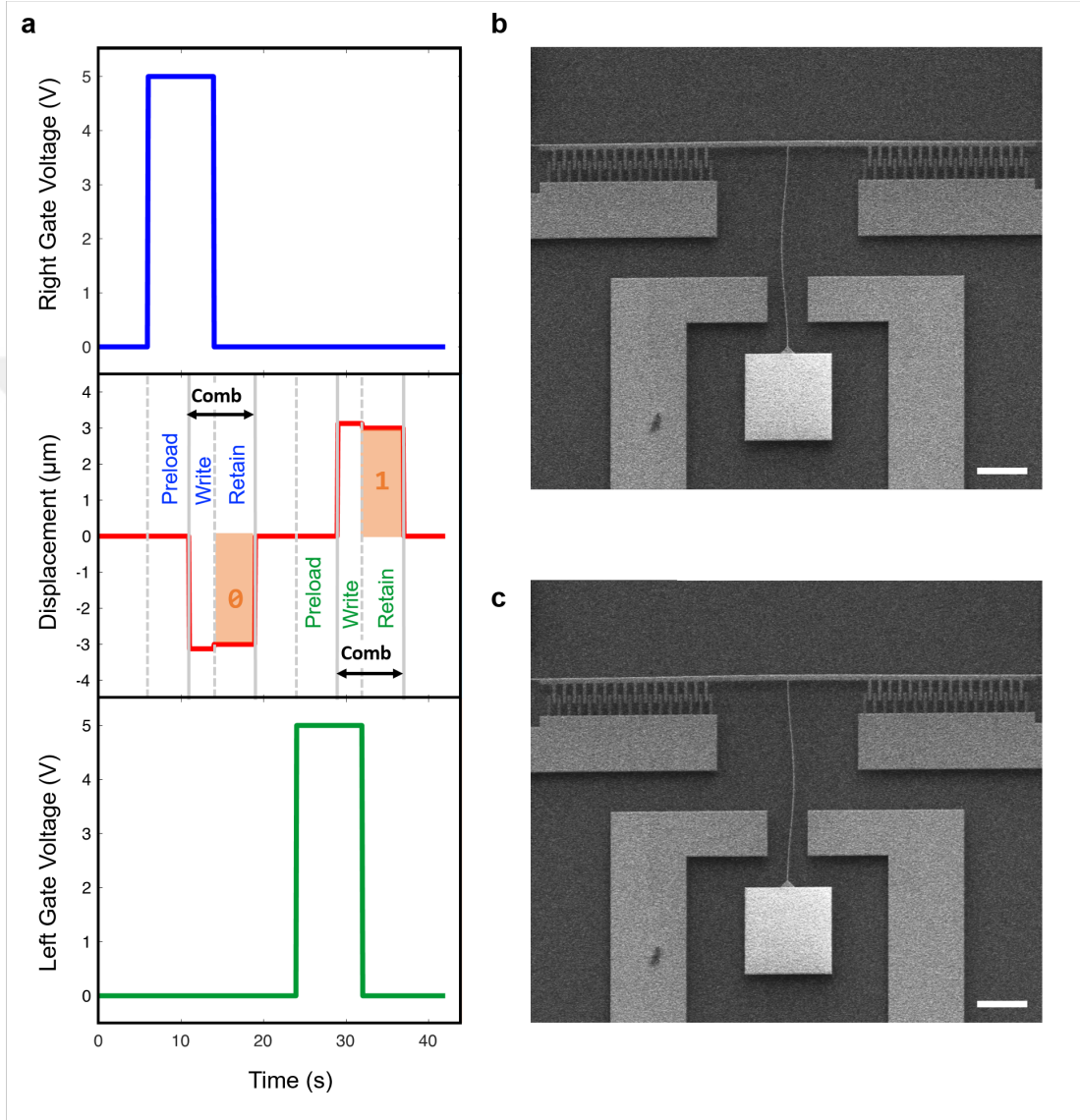


Figure 4.4: Information storage with nanoscale buckling. (a) Protocol to write information on the device. The top (bottom) panel shows the right (left) side gate control voltage waveform, while the middle panel shows the deflection of the centre of the beam as measured under SEM. The black arrow indicates when the comb drive actuators are activated. Orange shaded region shows information storage where the control signal is removed but the beam retains the information through buckling its direction. (b),(c) Demonstration of sub-1 V memory “bits” where the buckling direction can be controlled just by applying 0.5 V on the left gate in (b) and the right gate in (c). Video 4 shows the dynamics of the process; the scale bars are 10 μm .

We have tested side gate voltages used as digital electronics standards (5 V, 3.3 V, 2.5 V and 1.8 V) and in all cases, the buckling direction was determined by these voltages (Video 1). Moreover, in the designs where the side gates are placed in a way to increase capacitive coupling (i.e. longer electrodes positioned near the centre), we have observed that a side gate voltage as low as 0.5 V is sufficient to store information in the beam (Fig. 4.4b,c and Video 4). Although a large comb-drive voltage (~ 45 V) is still required to exert the necessary compression force, it is independent of the information transfer – i.e., it has no informatics entropy. Thus, data transfer can be accomplished by applying sub-1V signals between different computation units, such as from an external digital signal line to NEMS or within a CMOS-NEMS hybrid systems.[57] Further, the necessary force to guide the buckling direction (less than hundred pN) is small enough to enable multi-stage mechanical computation.

The displacement strongly depends on the comb drive voltage: the electrostatic force scales with the square of the comb drive voltage: $V_{stat} - V_{mov}$. [58] In this way, nanomechanical buckling opens up the way for a nanoscale manipulator that can reach large displacements with high precision (as steep as ~ 2 nm per mV, Fig. 4.5 and Video 2). In particular, the central point of the beam displaces ~ 4 microns by changing the voltage merely by ~ 7 Volts after the buckling threshold (Fig. 4.5b). This device paradigm offers an enormous flexibility in controlling the axial and lateral forces: the post-buckling behaviour can be fine-tuned by changing the corresponding voltages.

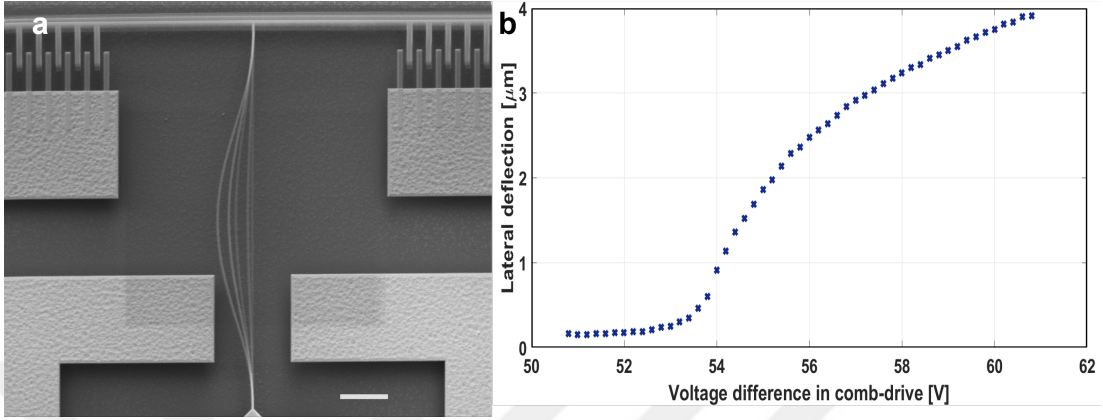


Figure 4.5: Post-buckling behaviour. (a) Displacements can be controlled by changing the comb drive voltage. Here multiple SEM images are over-laid to show the degree of control possible for positioning of the beam. The scale bar is 5 μm (b) Post-buckling curve.

4.2.1 Device Operation Repeatability and Reliability

We confirmed the repeatability and robustness of the buckling behaviour, even after more than 1000 bi-directional loading cycles with lateral deflections of $\sim 2.2 \mu\text{m}$ (Fig. 4.6a) and 10,000 mono-directional loading cycles with lateral deflections of $\sim 1.5 \mu\text{m}$ (Fig. 4.6b), with no apparent degradation in device performance. Moreover, we have shown reliable mechanical contact formation and detachment in Fig. 4.7 and Video 5. We intentionally buckled the beam forcibly so that it contacts a side gate, then we decreased the comb drive voltage: the beam recovered back to the unbuckled state owing to the restoring force provided by the buckled beam and modified crab leg design. These features present a clear advantage over the pull-in based nanomechanical contact switches where stiction constitutes an important obstacle[59] and active research problem.[60]

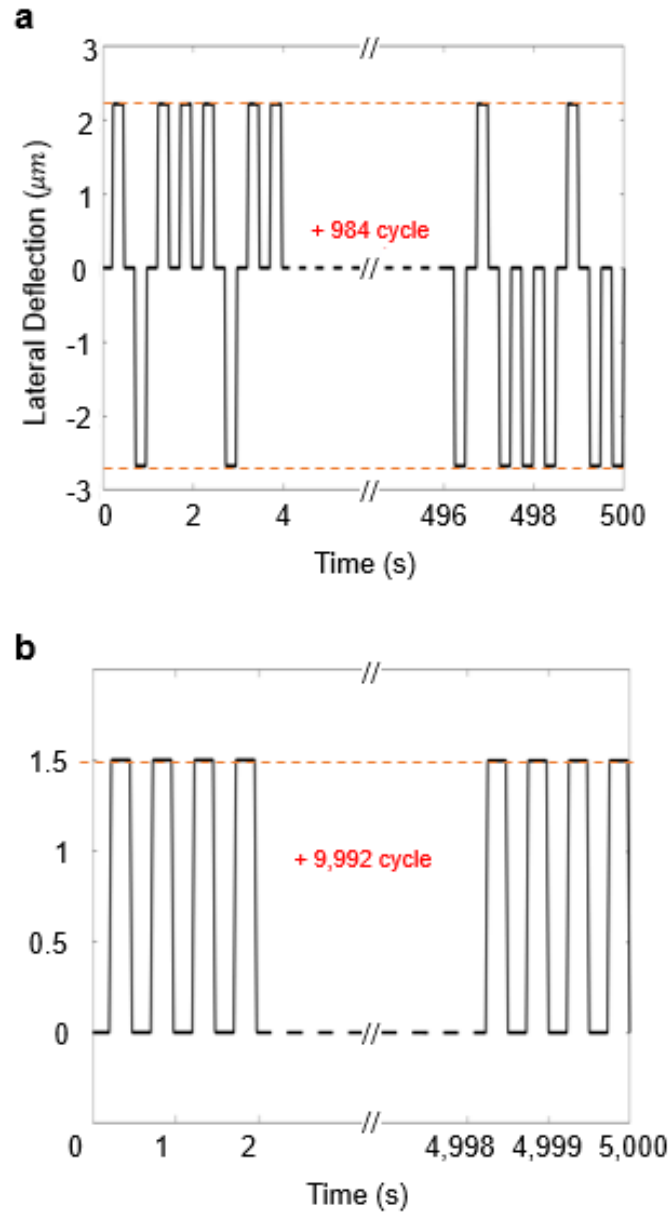


Figure 4.6: (a) 1000 bi-directional loading with 2 Hz square wave actuation. (b) 10,000 mono-directional loading with 2 Hz square wave actuation.

For the purpose of conducting a fracture test, a device is loaded cyclically by employing a square wave with a frequency of 2 Hz and to make sure about that all individual cycles completed successfully, test is recorded in the SEM (Fig. 4.6a-b). Low frame rate of the SEM is the limiting factor of actuation frequency.

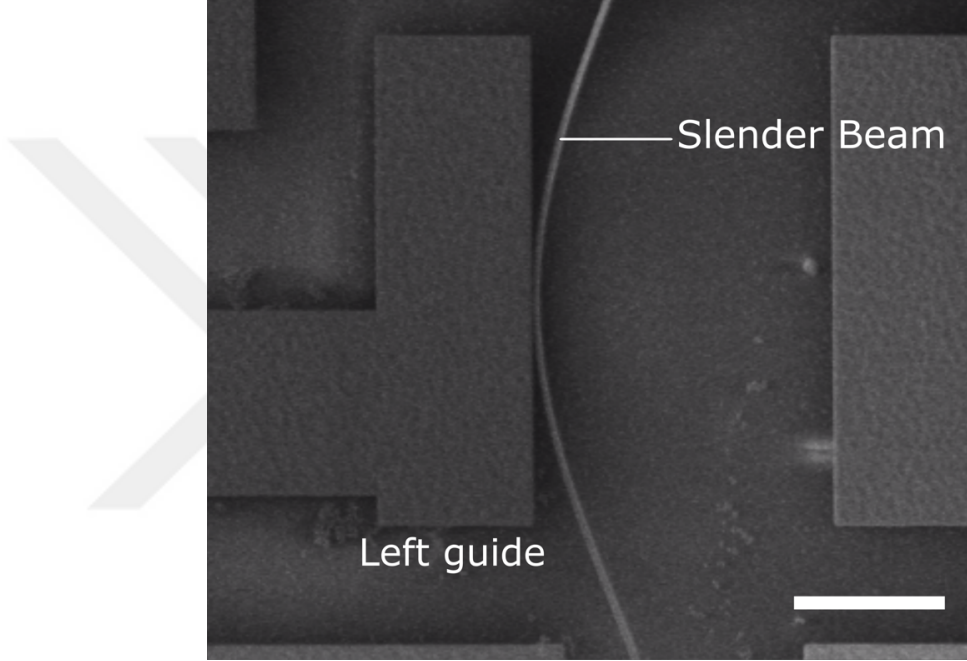


Figure 4.7: Retractable contact forming between the beam and the side gate. Scale bar is 5 μm .

4.2.2 Potential Energy Barrier Control

We have dynamically changed the potential energy landscape of the beam using the control voltages (Fig. 4.8a,b). The barrier height between the bistable states can be tuned by changing the $(V_{mov}-V_{stat})$, and the asymmetry between the states can be modified by adjusting the $(V_{right}-V_{left})$ as shown in Fig. 4.8a,b. When the barrier is lowered, and the control voltage is fine-tuned, repeated erratic transitions emerge between the two buckled states, as shown in Fig. 4.8c and in Video 6 and 7. Additionally, in Fig. 4.8c, the beam appears as if is at two different states simultaneously, due to SEM image rendering.

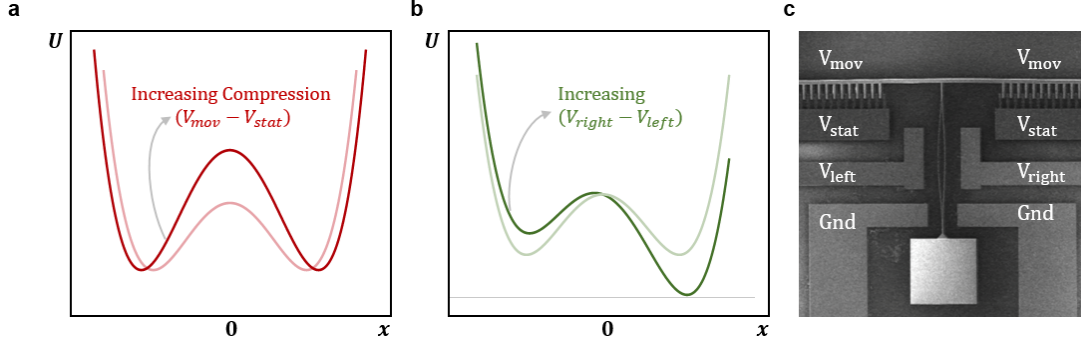


Figure 4.8: Transition between buckling states. (a,b) The potential energy barrier can be adjusted by changing the compressive force through V_{mov} and V_{stat} . The asymmetry between the wells can be adjusted by changing the lateral force through V_{right} and V_{left} (assuming a constant beam voltage). (c) Snapshot of erratic transitions between the two bistable states. The beam appears as if at two positions, since SEM renders an image by averaging several frames while the device rapidly transits between the two states. Video 6 and 7 clearly show the dynamics of transitions.

This unstable regime should be avoided for memory storage operations, since the information may be lost due to an uncontrollable switching between the states. Indeed, the limiting factor for the minimum side gate voltage, apart from fabrication asymmetries, is that the thermomechanical noise in the force domain gets comparable to the force generated by control voltages. For instance, when 0.5 V is used as side gate voltage, it is apparent in some frames in Video 4 (second 10) that the beam initially attempts to buckle towards the opposite direction of the control voltage (in this case when the moving comb (and beam) is loaded with -20 V, $F_{(side-gate)}=25$ pN which is demonstrated in Fig. 4.9 and $F_{(noise-rms)}=12$ pN whose calculation is shown in Appendix B).

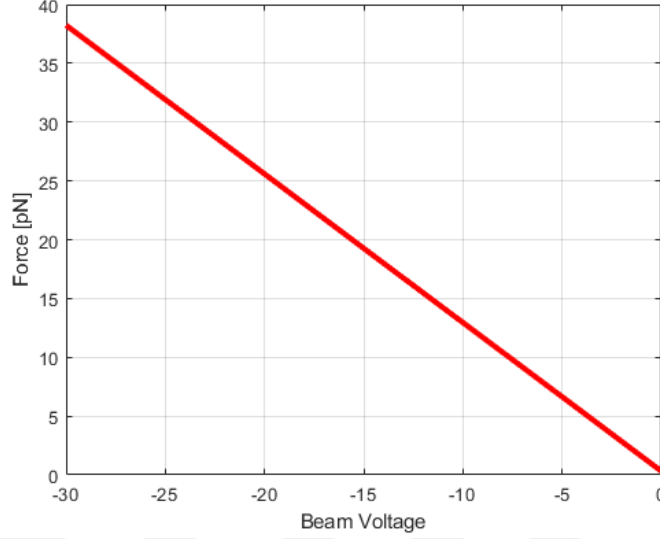


Figure 4.9: Lateral force affecting the beam when 0.5 V is given to side gate.

Generally, snap-through transitions exhibit a hysteresis curve where the forward and backward jumps occur at different gate voltages (Fig. 4.10 and Video 8). The snap-through transitions between the left and right buckled states are predicted to be enhanced due to fabrication imperfections at the nanoscale.[42] However, at certain parameters of comb and side gate voltages, we have observed persistent transitions between two states (Video 6 and 7). Similar repeated transitions between buckled states were observed in a recent optomechanical experiment and was attributed to technical noise.[32] The noise sources in our experiment is not limited to the thermal noise: observation under SEM introduces high-energy electron bombardment which may serve as a source of excitation. We also note that the inertia and elasticity of the bar holding the movable electrodes can also affect the overall dynamics.

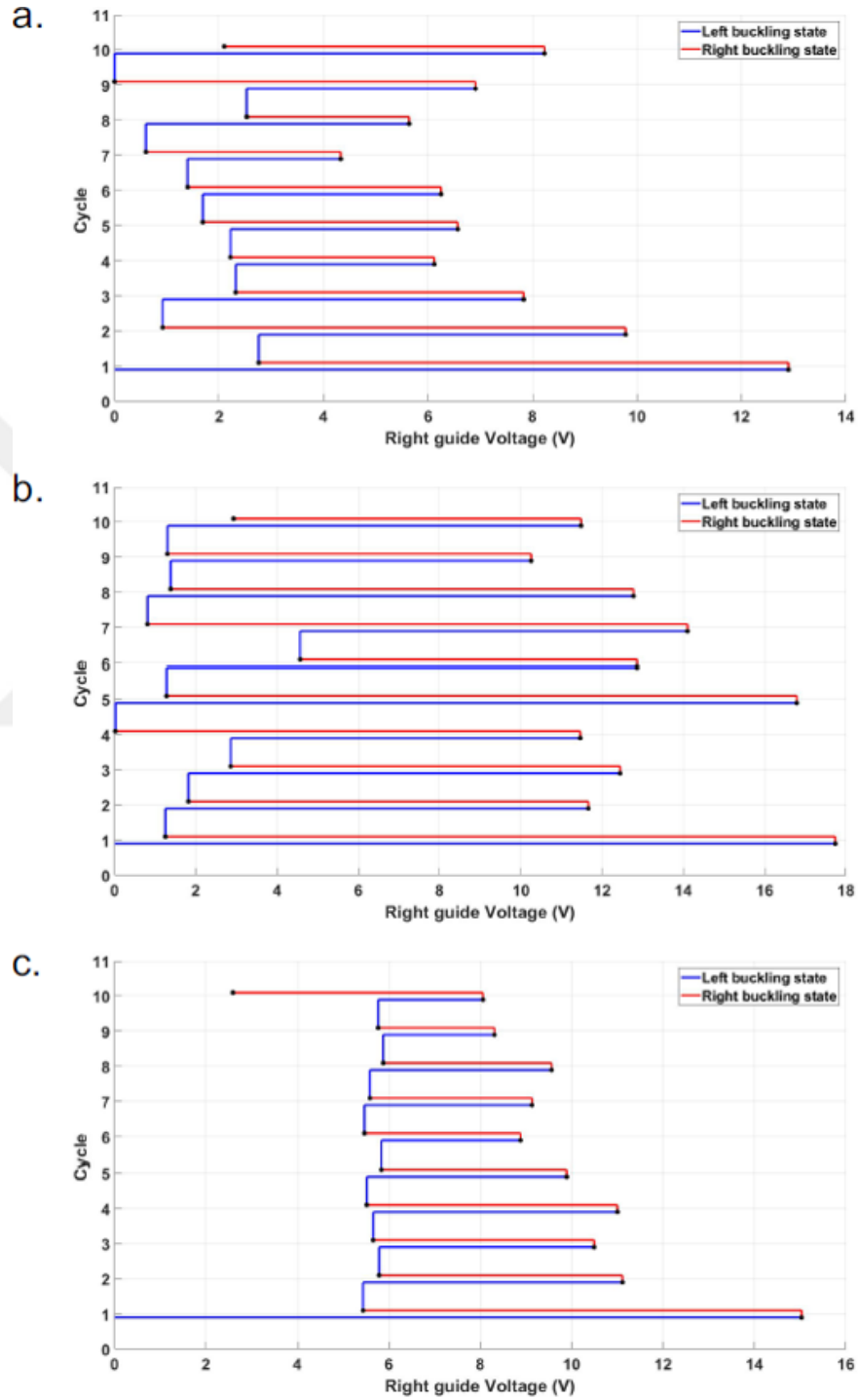


Figure 4.10: Hysteresis curves between the left and right buckling states. The left-to-right transition occurs at much larger gate voltages compared to the right-to-left transitions. The comb drive voltages are (a) 56.5 V, (b) 57.0 V and (c) 57.5 V.

4.3 Buckling Experiment Using Microwave Resonator for Readout

After completing the above characterisation of the nanomechanical buckling behaviour by SEM, we next considered the electronic readout of a bit of information. Since it is challenging to detect positional changes at these dimensions, we have developed a special readout circuitry. The readout is based on detecting a change in the capacitance between the buckling beam and one of the side gates (Fig. 4.11).

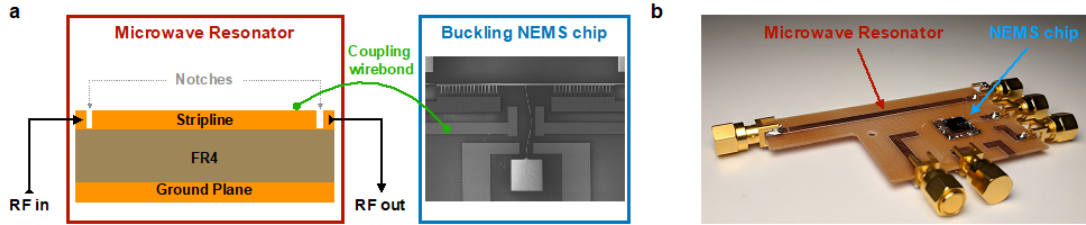


Figure 4.11: Electronic readout of buckling. (a) Wiring diagram: an open-ended micro stripline resonator is wire bonded to a side gate of a buckling NEMS beam. (b) Picture of the microwave readout PCB, the electronic access is provided by standard SMA ports.

An open ended microstripline resonator composed of copper and FR4 is utilized to measure the buckling deflection and direction via the coupled capacitive gate. During the measurement, microstripline resonator is driven on a Phase Locked Loop (PLL) that is extremely sensitive to resonance frequency changes of the stripline (Allan Deviation is 7×10^{-7}). Throughout the experiment, static combs are kept at +30 V and no guide voltage is used since the beam inherently buckles away from the gate used for readout. For actuating the system, an Arduino Nano is used to produce a square wave which switches a relay periodically. The relay provides to mobile combs -16 V when de-energized and -22 V when energized. When $V_{mov} = -16$ V the voltage difference between the static and mobile combs are below the threshold and the beam is unbuckled. In contrast, when $V_{mov} = -22$ V the voltage difference is large enough to initiate buckling. We have independently verified beam buckling using an optical microscope under atmospheric condition, just before we perform the microwave experiment.

The observed deflection is estimated to be $2\text{ }\mu\text{m}$ for these parameters under the microscope – by comparing the deflection to other features of known size on the active region of the chip. We have performed control experiments where the relay switched between $V_{mov} = -10\text{ V}$ and $V_{mov} = -16\text{ V}$, thus keeping the voltage difference between the on/off states of the electrical stimulus the same, whereas the beam stays in the unbuckled configuration in both states. No discernible change was observed in the PLL run for the control run as expected.

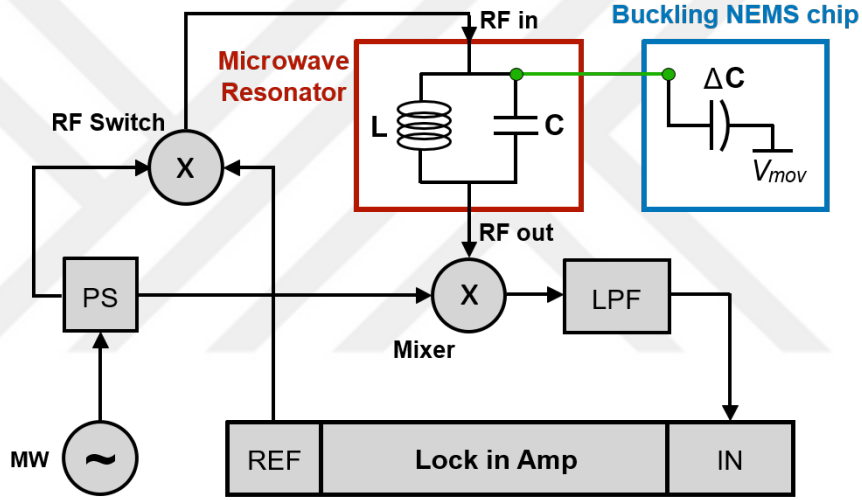


Figure 4.12: Frequency-tracking circuit. The signal from a microwave source (MW) is modulated by the reference channel (REF) of a lock-in amplifier, which then excites a microwave resonator. The microwave resonator is capacitively coupled to a buckling NEMS chip. The output from the resonator is down mixed to the lock-in frequency, low-pass filtered (LPF) and read by the lock-in amplifier. PS denotes Power Splitter.

As the beam buckles away from the side gate used for readout, the resultant capacitance of the microstrip line resonator decreases and the resonance frequency increases which can be detected accurately[61, 62] (Fig. 4.12,4.13). In the detection scheme, the microstrip line resonator was driven by a function generator to its resonance, and the phase response is measured continuously. As the frequency of the resonator changes (e.g. due to the buckling) then the phase of the resonator moves away from the reference value, which is detected and restored by a feedback loop. Therefore, the motional changes of the buckling beam can be detected as frequency shifts. As shown in Fig. 4.13, the stored information

can be successfully retained for several seconds.

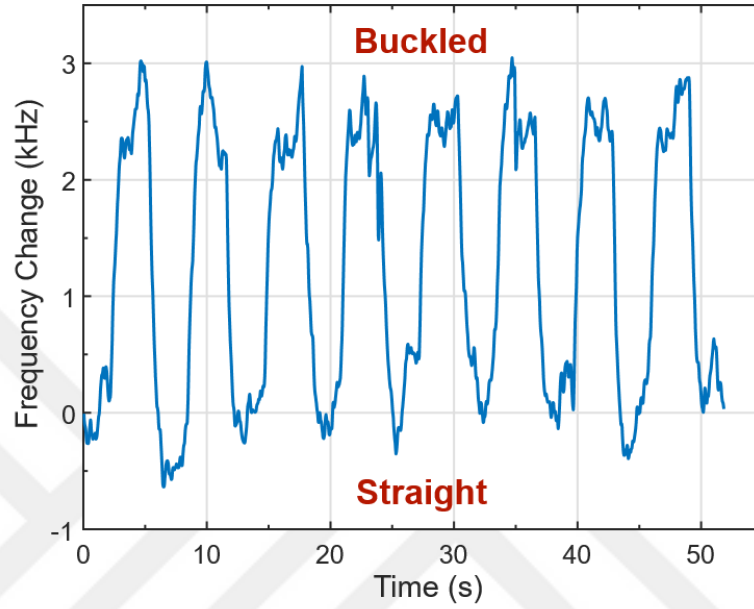


Figure 4.13: Change in frequency as a function of time while the beam buckles periodically. The frequency of the resonator is 1.398 GHz which is subtracted from y-axis.

Chapter 5

Conclusion and Future Work

In this study, a nanomechanical platform to store information and study rich dynamics near bifurcations have been developed. For such explorations, the tunability of the compressive force, without significant heat generation on the device, is critical for tuning the potential energy landscape as desired. Building on the device paradigm here, multibit operations and two-dimensional nanomechanical positioning systems with multiplexed readout are possible. Finally, the mechanism, which can be controlled with a simple protocol and does not generate heat, can be used for nano-manipulation[63] and on-demand single-cell mechanical lysis applications.[64]

5.1 Prospects of Buckling Based Nanomechanical Systems

We have shown that buckling can be controlled at the nanoscale just by using DC voltages to create electrostatic fields. In this way, the instrumentational complexity to use buckling without significant heat generation in device applications (memory, positioning etc.) decreases. The ability to determine the compressive force is critical to tune the device functionality, as buckling transitions between

different states emerge when we decrease the potential energy barrier. Now it is discussed how the demonstrated device function and performance fit into the current context and what the possible ways to improve device capabilities are.

5.1.1 Integration Density

In this proof-of-principle demonstration, we have worked with a single buckling unit. The device fits into an area of 150 microns by 60 microns excluding bonding pads. Therefore, the integration density is about 11 thousand devices per cm^2 which is sufficient for various niche applications of mechanical switches, such as hybrid NEMS-CMOS RAMs,[59] high-temperature embedded systems, and multiplexed manipulators/positioners e.g. for cell handling in a lab-on-a-chip system. It is feasible to actuate many buckling beams by the same comb drive mechanism for compact and synchronous operation. For example, each beam can be fabricated to be 20 nm wide using EBL, which would reduce the required force to buckle each beam can be reduced by more than two orders of magnitude. The force scaling provides an order-of-magnitude decrease in terms of actuation voltage. With the expected scaling, the device density can be increased ten-fold in linear dimensions to 1.1 million devices per cm^2 .

5.1.2 Compression Force and Voltage Requirements

The critical force to initiate buckling depends on the material strength and geometrical properties. The corresponding voltage to reach the critical force depends on the number of fingers and gap between them. Therefore, there are many parameters to optimize —such as the width of the beams, the density and number of fingers— in order to decrease the voltages at levels compatible with digital electronics. We note that as the cross-sections of the buckling beams decrease (e.g. to increase integration density), surface effects will become more significant in determining critical force and post-buckling parameters.[65]

5.1.3 Power Consumption

The proposed device has very small static power consumption — only limited by the leakage current. With the current device, we measured and estimated a power consumption on the order of 1nW; however, most of this value originates from the current leakage through the large bonding pads. If we consider the leakage through the active region of the device only, this figure decreases down by three orders of magnitude, to 1pW per bit. This level is not only billion times smaller than thermally-induced buckling, it is also favourable over resonator based mechanical computers since driving the resonator, with a finite Q , continuously necessitates the dissipation of power.

The switching power consumption is 35 fJ / switch which is mainly determined by the resistive losses on the comb drive electrodes during charging/discharging. The parameters discussed above to decrease the comb drive voltages — comb drive finger number and intensity, width of the beam—can again decrease the power consumption by several orders of magnitude, placing the proposed design near the switching consumption of CMOS devices.[59]

5.1.4 Speed of Operation

We consider two timescales to determine the speed of operation: RC time constant associated with the comb drive charging, and the mechanical time scale for jumping between two bistable states. For the RC time scale —excluding the parasitic capacitance of cables and contact pads which are inevitable in prototypes—the current design has 700 aF comb drive capacitance and about 10 MegaOhms of resistance (determined by the thin SOI region of the crab legs), indicating an RC time scale of nanoseconds. Clearly, the charging rate in between stages can be increased by using a higher conductivity SOI or increasing the width conductivity-limiting of junction regions. For determining the mechanical time constant, one needs to know the damping factor of the mechanical beam. The damping factor for buckling will further be complicated by any plastic deformation and large

displacements involved. However, considering the ringdown times of nanomechanical systems of similar size and composition, one expects switching times on the order of tens of kilohertz. However, innovative material designs to decrease the response time of nanomechanical systems can increase these prospects.[66]

5.1.5 Reliability

Although the beam experiences very large displacements, we have shown that the device performance does not change within 10,000 cycles (limited by the duration of experiments under SEM environment). Considering that stiction and time-varying operation characteristics are detrimental for most mechanical switch designs, buckling can provide a new avenue for mechanical computation.

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Appendix A

Buckling Deflection Analysis Based on Euler-Bernoulli Beam Theory

A clamped-clamped beam compressed by a load P with an amount of tip displacement (δ) to a final horizontal length of L_f results in mode shape $U(x)$ is demonstrated in the following figure.

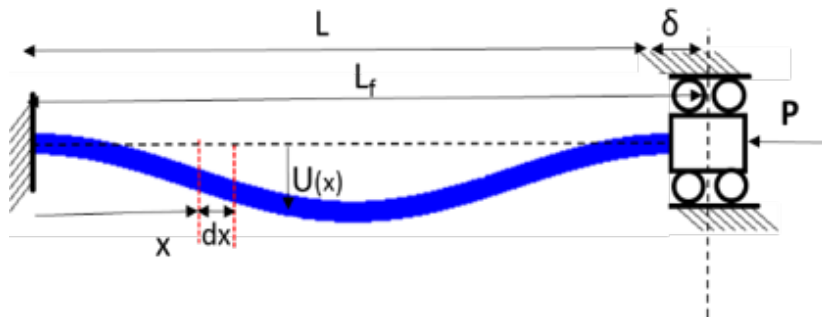


Figure A.1: Deflected Clamped-Clamped Beam

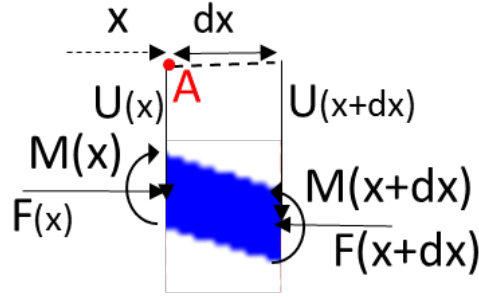


Figure A.2: Infinitesimal Beam Slice

Force equilibrium:

$$F(x) = F(x + dx) = P \quad (\text{A.1})$$

Moment equilibrium around A:

$$M(x + dx) - M(x) - u(x + dx)P + u(x)P = 0 \quad (\text{A.2})$$

Which can be adjusted as:

$$M(x + dx) - M(x) = P[u(x + dx) - u(x)] \quad (\text{A.3})$$

$$\frac{M(x + dx) - M(x)}{dx} = P \left[\frac{u(x + dx) - u(x)}{dx} \right] \quad (\text{A.4})$$

$$\frac{d(M(x))}{dx} = P \frac{d(u(x))}{dx} \quad (\text{A.5})$$

Recall

$$M(x) = -EI \frac{d^2(u(x))}{dx^2} \quad (\text{A.6})$$

then

$$-EI \frac{d^3(u(x))}{dx^3} = P \frac{d(u(x))}{dx} \quad (\text{A.7})$$

$$u'''(x) = -\frac{P}{EI} u'(x) \quad (\text{A.8})$$

Let

$$k^2 = \frac{P}{EI} \quad (\text{A.9})$$

then

$$u'''(x) = -k^2 u'(x) \quad (\text{A.10})$$

Characteristic polynomial:

$$\lambda^3 = -k^2 \lambda \quad (\text{A.11})$$

$$\lambda_1 = 0, \lambda_2 = ki, \lambda_3 = -ki \quad (\text{A.12})$$

$$u_1 = \text{constant}, u_2 = \cos(kx), u_3 = \sin(kx) \quad (\text{A.13})$$

General solution:

$$u(x) = C_1 \sin(x) + C_2 \cos(x) + C_3 \quad (\text{A.14})$$

Boundary Conditions:

$$BC1 : atx = 0, u(x) = 0 \quad (\text{A.15})$$

$$BC2 : atx = 0, u'(x) = 0 \quad (A.16)$$

$$BC3 : atx = L_f, u(x) = 0 \quad (A.17)$$

$$BC4 : atx = L_f, u'(x) = 0 \quad (A.18)$$

Put general solution (14) into the boundary conditions:

$$BC1 : 0 + C_2 + C_3 = 0 \quad (A.19)$$

$$BC2 : C_1 k - 0 + 0 = 0 \quad (A.20)$$

$$BC3 : C_1 \sin(kL_f) + C_2 \cos(kL_f) + C_3 = 0 \quad (A.21)$$

$$BC4 : C_1 \cos(kL_f) - C_2 \sin(kL_f) = 0 \quad (A.22)$$

Then from (19)

$$C_3 = -C_2 \quad (A.23)$$

from (20)

$$C_1 = 0 \quad (A.24)$$

from (19) and (21)

$$\cos(kL_f) = -1 \quad (A.25)$$

from (22)

$$\sin(kL_f) = 0 \quad (A.26)$$

In order to satisfy both (25) and (26)

$$kL_f = 2pnn : integer \quad (A.27)$$

Here $\mathbf{n}$ determines the mode number and general solution becomes:

$$u(x) = \frac{B}{2} \left[1 - \cos \left(\frac{2\pi n}{L_f} x \right) \right] \quad (A.28)$$

The constant (C_2) is represented as $\frac{B}{2}$ for convenience so that B becomes the maximum displacement at the midpoint. As the most observable mode is the first mode for many cases n is taken to be 1 for the rest of this paper yet the steps can be replicated for other mode numbers.

Solving for the indeterminate relations:

The general solution includes B and L_f whose relation to P is indeterminate within the general solution. Although the relation of L_f to P can be found from (9) and (27) for any given mode number, another physical relation is required between B and P. The length of the curved beam (S) is changed by the strain.

$$S = L(1 - \varepsilon) \quad (A.29)$$

Combining (9) and (27) for mode 1 ($n=1$):

$$\sqrt{\frac{P}{EI}} L_f = 2\pi \quad (A.30)$$

The strain in a beam is:

$$\varepsilon = \frac{P}{EA} \quad (A.31)$$

Then combining (30) with (31)

$$\varepsilon = \frac{\pi^2 h^2}{2L_f^2} \quad (A.32)$$

However in post buckling condition (32) does not hold true.[67] Fang said: "It is observed that the buckling causes softening such that a load P_2 which is smaller than P can hold the beam in position in post buckling condition which is indeterminate" [67], thus small strain assumption will be done for the following equations whose reliability is examined in assumptions part.

The length of the curved beam (S) can also be derived from the mode shape as follows:

$$S = \int_0^{L_f} \sqrt{\left(\frac{d(u(x))}{dx}\right)^2 + 1} dx \quad (\text{A.33})$$

From (28) and (33)

$$S = \int_0^{L_f} \sqrt{\frac{B^2 \pi^2}{L_f^2} \sin^2\left(\frac{2\pi}{L_f}x\right) + 1} dx = L \quad (\text{A.34})$$

From (33) the following plots are made for different tip displacement of the beam. The compression rate is defined as the rate of tip displacement (δ) to the initial length (L_0) of the beam.

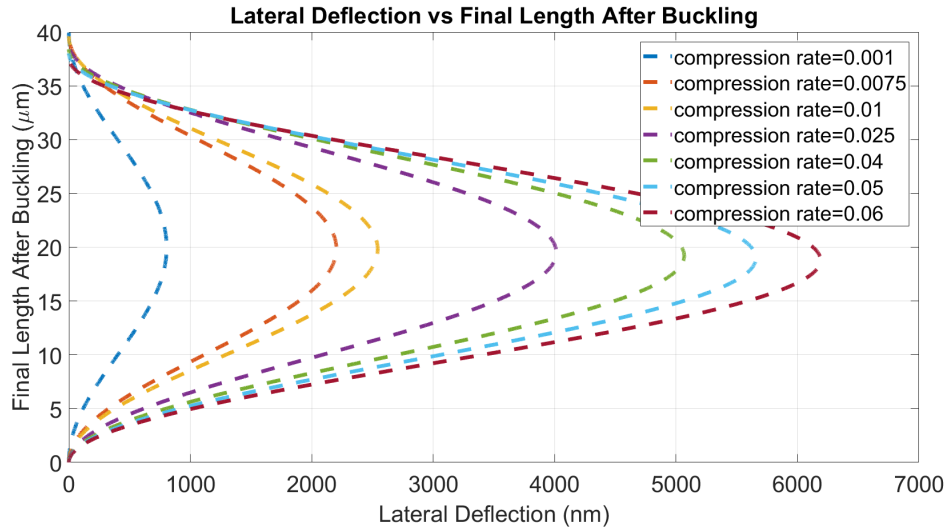


Figure A.3: Buckling of the beam corresponding to different compression rates

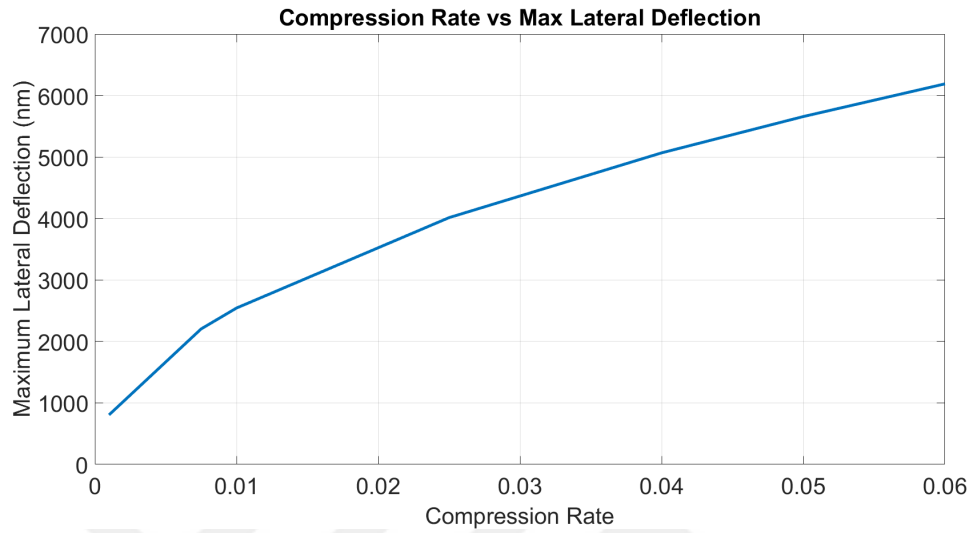


Figure A.4: Maximum buckling amount of the midpoint of the beam at different compression rates

The design of the buckling beam structure is made considering these plots and calculations and it is observed that the results satisfy these as shown the Fig. A.5.

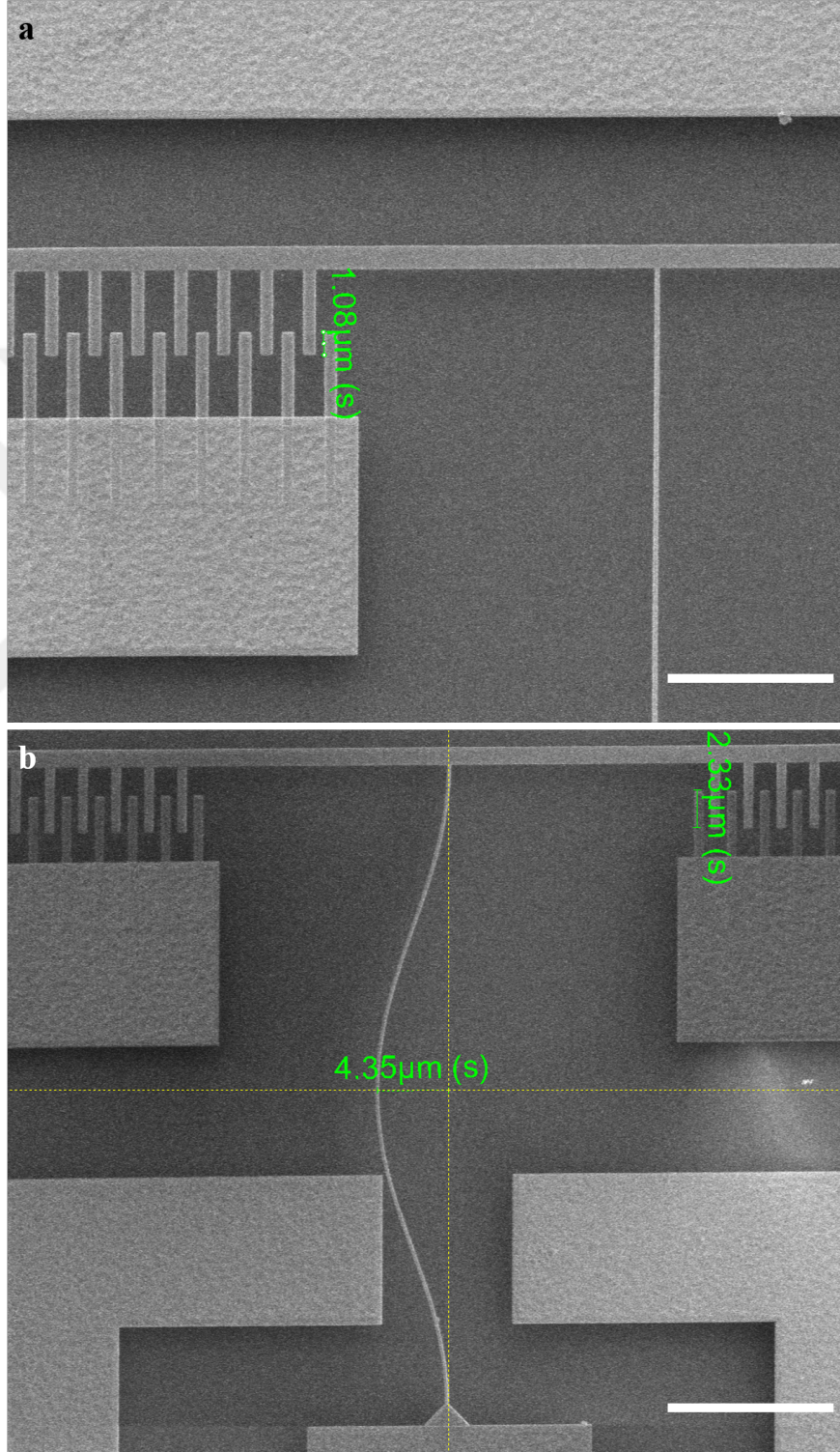


Figure A.5: (a) Combs stand at uncompressed state. (b) When combs are compressed as $\delta = 1.25 \mu\text{m}$ and the compression rate is 0.03, the maximum deflection at the midpoint of the buckling beam is $4.35 \mu\text{m}$ which satisfies the fig A.4 plot. Scale bars are $10 \mu\text{m}$.

Appendix B

Calculations of F_{rms} from Equipartition Theorem

Equipartition equation of one directional system:

$$\frac{1}{2}k_B T = \frac{1}{2}kx^2 \quad (\text{B.1})$$

$$F = kx \quad (\text{B.2})$$

$$k_B T = k \frac{F^2}{k^2} \quad (\text{B.3})$$

$$F_{rms} = \sqrt{k_B T k} \quad (\text{B.4})$$

For clamped-clamped beam:

$$k = \sqrt{\frac{16Ew^3h^3}{L^3}} \quad (\text{B.5})$$

Then,

$$F_{rms} = \sqrt{\frac{16Ew^3h^3k_BT}{L^3}} \quad (\text{B.6})$$

when $E = 169GPa$, $w = 250nm$, $h = 150nm$, $k_B = 1.38 \times 10^{-23}J/K$, $T = 300K$ and $L = 40\mu m$ are put in the equation B.7:

$$F_{rms} \approx 12pN \quad (\text{B.7})$$

Appendix C

Codes

C.1 Figure A.3 and Figure A.4 Code

```
clc
clear
format long

L = 40e-6;
del=[ 0.001,          0.0075          0.01,
0.025          0.04,          0.05
0.06,          ];
b=[4.025833393163    11.016196911599    12.7163905122546
20.0678905897588    25.3346116978195    28.2875765212425
30.9461048551777    ]*1e-7;
U=[];
Y=[];
Umax=[];
for i =1:length(del)
L_final = L*(1-del(i));
```

```

B = b(i);
y = linspace(0,L_final,10000);
Y=[Y;y];
u = (B*cos(2*pi*y/L_final)-B );
U=[U;u];
umax=u(10000/2);
Umax=[Umax,umax];
end
U=-U*1e9;
Y=Y*1e6;
figure(1)
plot(U(1,:),Y(1,:), 'LineWidth',3)
%axis([0,1.5e-6,0,5e-6])
legend(['compression rate=' num2str(del(1)) ])
grid on
pause(1)
plot(U(1,:),Y(1,:), '--',U(2,:),Y(2,:), 'LineWidth',3)
%axis([0,1.5e-6,0,5e-6])
legend(['compression rate=' num2str(del(1)) ],...
['compression rate=' num2str(del(2)) ])
grid on
pause(1)
plot(U(1,:),Y(1,:), '--',U(2,:),Y(2,:), '--',U(3,:), ...
Y(3,:), 'LineWidth',3)
%axis([0,1.5e-6,0,5e-6])
legend(['compression rate=' num2str(del(1)) ], ...
['compression rate=' num2str(del(2)) ],['compression ...
rate=' num2str(del(3)) ])
grid on
pause(1)
plot(U(1,:),Y(1,:), '--',U(2,:),Y(2,:), '--',U(3,:), ...
Y(3,:), '--',U(4,:),Y(4,:), 'LineWidth',3)
grid on

```

```

legend([ 'compression rate=' num2str(del(1)) ], ...
[ 'compression rate=' num2str(del(2)) ],[ 'compression ...
rate=' num2str(del(3)) ],[ 'compression rate=' ...
num2str(del(4)) ])
%axis([0,1.5e-6,0,5e-6])
pause(1)
plot(U(1,:),Y(1,:), '--',U(2,:),Y(2,:), '--',U(3,:), ...
Y(3,:), '--',U(4,:),Y(4,:), '--',U(5,:),Y(5,:), 'LineWidth',3)
legend([ 'compression rate=' num2str(del(1)) ], ...
[ 'compression rate=' num2str(del(2)) ],[ 'compression ...
rate=' num2str(del(3)) ],[ 'compression rate=' ...
num2str(del(4)) ],[ 'compression rate=' num2str(del(5)) ])
grid on
%axis([0,1.5e-6,0,5e-6])
pause(1)
plot(U(1,:),Y(1,:), '--',U(2,:),Y(2,:), '--',U(3,:), ...
Y(3,:), '--',U(4,:),Y(4,:), '--',U(5,:),Y(5,:), '--', ...
U(6,:),Y(6,:), 'LineWidth',3)
legend([ 'compression rate=' num2str(del(1)) ], ...
[ 'compression rate=' num2str(del(2)) ],[ 'compression ...
rate=' num2str(del(3)) ],[ 'compression rate=' ...
num2str(del(4)) ],[ 'compression rate=' num2str(del(5)) ], ...
[ 'compression rate=' num2str(del(6))])
grid on
% axis([0,1.5e-6,0,5e-6])
pause(1)
plot(U(1,:),Y(1,:), '--',U(2,:),Y(2,:), '--',U(3,:), ...
Y(3,:), '--',U(4,:),Y(4,:), '--',U(5,:),Y(5,:), '--', ...
U(6,:),Y(6,:), '--',U(7,:),Y(7,:), '--', 'LineWidth',4)
legend([ 'compression rate=' num2str(del(1)) ], ...
[ 'compression rate=' num2str(del(2)) ],[ 'compression ...
rate=' num2str(del(3)) ], [ 'compression rate=' ...
num2str(del(4)) ], [ 'compression rate=' num2str(del(5))], ...

```

```

[ 'compression rate=' num2str(del(6)) ],[ 'compression ...
rate=' num2str(del(7)) ])
% axis([0,1.5e-6,0,5e-6])
grid on
set(gcf,'units','points','position',[500 0 250 1500])
set(gca,'FontSize',16)
xlabel('Lateral Deflection (nm)','FontSize',20)
ylabel('Final Length After Buckling (um)','FontSize',20)
title('Lateral Deflection vs Final Length After Buckling', ...
'FontSize',24)

figure(2)
plot(del,-Umax*1e9,'LineWidth',3)
grid on
set(gca,'FontSize',16)
xlabel('Compression Rate','FontSize',20)
ylabel('Maximum Lateral Deflection (nm)','FontSize',20)
title('Compression Rate vs Max Lateral Deflection', ...
'FontSize',24)

```

C.2 Buckling Force/Voltage - Crab Leg Spring Design Code

```

%% For Desing 1 with 500 nm comb width

clc
clear
format long

%%General Parameters
L = 40e-6;
E = 150*10^9;

```

```

h = 150*10^-9;
b = 250*10^-9;
I = (1/12)*b*h^3;
Area = h*b;

%% 5% comp
L_final = 0.975*L;
B = (20.067890589759e-7);
eps = pi^2*h^2/(3*L^2);
P_crit = 4*pi^2*E*I/(L^2)
Mo = B*P_crit;

fun = @(y) sqrt(B.^2*(2*pi/L_final)^2* ...
(sin(2*pi*y/(L_final))).^2+1);

A = integral(fun,0,L_final)

syms y

u = symfun(B*cos(2*pi*y/L_final)-B , y);

y = linspace(0,L_final,1000);

plot(-u(y)*1e6,y*1e6,'LineWidth',3) %compression vs lateral def
grid on
xlabel('lateral deflection (um)')
ylabel('L_{final}(um)')
title 'L_{final} vs Lateral Deflection '

t_comb = 250e-9;
t_spring = 200e-9;
w_spring = 250e-9;

```



```

perm = 8.854*10^-12; %constant
g = 500e-9;
N = 32;
V = 43;

delta_y = L-L_final

F_onecomb = V^2*perm*t_comb/(g);

F_comb = V^2*perm*N*t_comb/(g)

% %% Fixed Spring
% L_spring = ((4*delta_y*E*w_spring*(t_spring^3))/ ...
(F_comb/2))^(1/3)
%
% I_1 = (1/12)*w_spring*t_spring^3;
% str_fix=((F_comb/2)*L_spring)*(t_spring/2)/I_1
%

%% Crab Leg (Legdenberg)

I_1 = (1/12)*w_spring*t_spring^3;
I_2 = (1/12)*w_spring*t_spring^3;

k_y = F_comb/delta_y %F=k*y

overlaps = 1e-6;

%k_instability = (2*N*perm*t_spring* ...
(overlaps+delta_y)*V^2)/(g^3)

L_1 = 13.5e-6;

```

$$L_2 = 5e-6;$$

$$\%K_x = (12 * E * I_2 / (L_2^3)) * ((L_1 * I_2 + L_2 * I_1) \dots \\ / (2 * L_1 * I_2 + L_2 * I_1))$$

$$K_y = (24 * E * I_1 / (L_1^3)) * ((L_1 * I_2 + L_2 * I_1) \dots \\ / (L_1 * I_2 + 4 * L_2 * I_1))$$

$$\text{str_crab} = ((F_{\text{comb}} / 2) * L_1) * (t_{\text{spring}} / 2) / I_1;$$