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MEASUREMENT OF THE PROPERTIES OF METALMUMPS® THIN FILMS

by

John Shih-Hua Chang

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Abstract

Measurement of the Properties of MetalMUMPs® Thin Films

Master of Applied Science, 2009

John Shih-Hua Chang

Mechanical Engineering, Ryerson University

The metal multi-user micro-electro-mechanical-systems (MEMS) processes (MetalMUMPs®) micro-machining process includes two silicon nitride films, one polysilicon film, and one nickel film for constructing various MEMS devices. This thesis presents property measurements of the MetalMUMPs® silicon nitride and nickel films. Fabricated MetalMUMPs® silicon nitride prototypes were used to experimentally determine a Young's modulus of 209 GPa and a residual stress difference of 169 MPa for the silicon nitride films. A method, which uses the deformations along the width of bi-layered cantilever beams, was proposed to determine the residual stress difference of the two silicon nitride films. Fabricated MetalMUMPs® nickel prototypes were used to experimentally extract a Young's modulus of 159 GPa and a residual stress gradient of $-4.72 \text{ MPa}/\mu\text{m}$ for the nickel film. A micro bridge mechanism was developed to lift long silicon nitride beams for the determination of the residual stress difference of the two silicon nitride films.

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Nomenclature

A = Area
b = Width
C_1 = A constant
CMOS = Complementary metal–oxide–semiconductor
CVD = Chemical Vapor Deposition
DLP = Digital Light Processing
DRIE = Deep reactive-ion etching
$\bar{E}$ = Effective Young's modulus
$\tilde{E}$ = Equivalent effective Young's modulus
E = Young's modulus
f = Frequency
F = Force
h = Thickness
HF = Hydrogen Fluoride

I = Moment of inertia
 IC = Integrated Circuit
 KOH = Potassium Hydroxide
 L = Length
 $LIGA$ = Lithographie, Galvanoformung, Abformung
 $LPCVD$ = Low Pressure Chemical Vapor Deposition
 M = Bending moment
 $MEMS$ = Micro-Electro-Mechanical Systems
 $MUMPs$ = Multi-User MEMS Processes
 N = Number of population data points
 OEM = Original Equipment Manufacturer
 PSG = PhosphoSilicate Glass
 PVD = Physical Vapor Deposition
 R_{FB} = Radius of curvature of the free beam
 R_w = Radius of curvature along the beam width
 RF = Radio Frequency
 RIE = Reactive Ion Etching
 SOI = Silicon on Insulator
 $\bar{x}$ = Population mean
 x_i = Data point value

Greek Letters

α_n = Eigenvalue for the resonance frequency mode
 Γ = Residual stress gradient
 $\Delta\sigma$ = Residual stress difference
 δ = Deflection
 ε = Strain
 θ = Angle
 ν = Poisson's Ratio
 π = Pi, mathematical constant
 ρ = Mass density
 Σ = Sum
 σ = Residual mean stress
 σ_p = Population standard deviation

Chapter 1 Introduction

1.1 What is MEMS?

Micro-electro-mechanical systems (MEMS) are integrated micro devices or systems combining electrical and mechanical components fabricated using processes similar to those used in making integrated circuits (ICs) in the semi-conductor industry [1]. MEMS devices have a size of less than one millimetre to several millimetres and largely consist of sensors and actuators [1]. Due to their small size, micro devices allow them to work in small areas to measure acceleration, strain, pressure, temperature, vibration and rotation [1]. MEMS technology is widely used in telecommunications, biomedical and healthcare, automobile industry, information and consumer electronics, and defence applications [1]. Several common MEMS products include inkjet printer cartridges, micro accelerometers (such as the airbag sensor used in cars, Figure 1.1a), MEMS gyroscopes (Figure 1.1b), micromirrors for digital light processing (DLP) displays (Figure 1.2a), car tire pressure sensors, blood pressure sensors (Figure 1.2b), MEMS microphone, MEMS RF switch (Figure 1.3), and MEMS infrared sensor and optical switching technology used in data communications [2][3].

a) Micro accelerometer

b) MEMS gyroscope

Figure 1.1 a) Micro accelerometer (Analog Devices, Inc.) [4], b) MEMS gyroscope (Analog Devices, Inc.) [5].

a) Micro mirror

b) Micro blood pressure sensor

Figure 1.2 a) Digital micromirror device (Texas Instruments, Inc.) [6], b) Micro blood pressure sensor (Fraunhofer-Gesellschaft) [7].

Figure 1.3 MEMS RF switch (Radant MEMS, Inc.) [8].

1.2 MEMS manufacturing technology

Micro-fabrication technology combines IC processes with highly-specialized micro-machining processes (e.g., photolithography, sputtering, doping, chemical vapour deposition (CVD), ion implantation, oxidation, diffusion, etc) to fabricate MEMS devices [1]. The electronics are fabricated using typical IC processes (e.g., complementary metal–oxide–semiconductor (CMOS) process) and the micro-mechanical components are fabricated using compatible micro-machining processes (e.g., deep reactive ion etching (DRIE)). The micro-machining processes either etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices [1].

MEMS devices are either fabricated using a custom micro-machining process or a commercially available micro-machining process. The custom micro-machining process fabricates the MEMS device by using processing steps developed by the MEMS user. The advantages of using a custom micro-machining process lies in the flexibility to modify the process to suit the design of the MEMS device and to experiment with different materials to fabricate the MEMS device. However, the drawbacks in using a custom micro-machining process are the high cost and the high risks involved in developing the process. Even with a successful custom micro-machining process, a limited number of MEMS prototypes can be fabricated. The commercially available micro-machining process manufactures the MEMS device by following a series of processing steps developed by the manufacturer. The commercially available micro-machining processes are developed to fabricate original equipment manufacturer (OEM) devices and are used by many MEMS users. The benefits of a commercially available micro-machining process are the low cost and low risk for the MEMS user. However, the design of the MEMS device is restricted by the methods and the materials of the commercially available micro-machining process, which limits the type of MEMS devices that can be fabricated.

A few examples of commercially available micro-machining processes are the poly multi-user MEMS processes (PolyMUMPs[®]) [9], silicon-on-insulator multi-user MEMS processes (SOIMUMPs[®]) [9], metal multi-user MEMS processes (MetalMUMPs[®]) [9], Sandia ultra-planar, multi-level MEMS technology 5 (SUMMiT VTM) [10], MicragemTM [11], silicon germanium (SiGe) bipolar complementary metal-oxide semiconductor (BiCMOS) [12], etc. In this thesis, the MetalMUMPs[®] micro-machining process is chosen for thin film property measurement.

1.3 MetalMUMPs®

MetalMUMPs® is the only commercial micro-machining process providing a thick structural metal film (a 20 μm nickel film plus a 0.5 μm top gold film) for constructing various MEMS devices [13]. Thus, the MetalMUMPs® process has been used for fabricating MEMS devices such as RF tuneable capacitors [14], RF inductors [15][16], RF switches [17], micro relays [18][19], a Cockcroft-Walton voltage multiplier [20], an electro-thermal actuator and thermal sensor [21], a 3-DOF gyroscope [22] and an electro-thermal actuated MEMS gripper [23].

The multi-user MEMS processes (MUMPs®) micro-machining technology is a commercial MEMS fabrication process that provides customers with cost-effective access to MEMS prototyping and a seamless transition into volume manufacturing [9]. MetalMUMPs® is an electroplated nickel micro-machining process derived from work performed at MEMSCAP Inc. (JDSU, Cronos, MCNC) throughout the 1990's. The process was originally developed for the fabrication of MEMS micro-relay devices based on a thermal actuator technology and was introduced to the market in 2003 [13]. MetalMUMPs® incorporates three major MEMS processes consisting of LIGA-like, thick metal electroplating, plus bulk and surface micromachining. The process consists of an electroplated nickel layer, which is used as the primary structural material and electrical interconnect layer, that can be built on top of a polysilicon film and two silicon nitride films with a deep, potassium hydroxide (KOH) etched trench in the silicon substrate [9][13] (see Figure 1.4).

Figure 1.4 Film layers in the MetalMUMPs[®] process [13].

In MetalMUMPs[®], the polysilicon can be used for resistors, additional mechanical structures, and/or cross-over electrical routing. The two silicon nitride layers are used for the mechanical connection and electrical insulation for suspending micro structures made of the nickel film [16][19][20]. The two silicon nitride films are either bonded together as a bi-layered structure or they sandwich the polysilicon film to form a tri-layered structure to suspend MetalMUMPs[®] devices. Deposited phosphosilicate glass (PSG) is used for the sacrificial layers. The trench in the silicon substrate can be incorporated for additional thermal and electrical isolation and a gold overplate can be used to coat the sidewalls of the nickel structures [13]. Details of the MetalMUMPs[®] design rules and process flow are found in the MetalMUMPs[®] design handbook [13].

1.4 Thesis objectives

The objective of this thesis is to measure properties of the MetalMUMPs[®] silicon nitride films and the MetalMUMPs[®] nickel film. The first property to be measured is the Young's modulus of the MetalMUMPs[®] silicon nitride. The second property to be determined is the residual stress difference of the two MetalMUMPs[®] silicon nitride films, which is not currently

available [24]. A residual stress difference between the two silicon nitride films causes undesired deformations and deteriorates the performance of MetalMUMPs[®] devices, which are suspended by silicon nitride bi-layer structures. In this thesis, a method, which uses the deformations along the width of bi-layered cantilever beams, is proposed to determine the residual stress difference of the two MetalMUMPs[®] silicon nitride films.

The third and forth properties to be extracted is the Young's modulus and the residual stress gradient across the thickness of the MetalMUMPs[®] nickel film, which are both not currently available [24]. Values of 202 GPa [14] or 180 GPa [25] are assumed for the Young's modulus of the nickel film by MetalMUMPs[®] users. Even with a small magnitude of the residual stress gradient across the thickness of the nickel film causes significant undesired deformations of suspended MetalMUMPs[®] nickel structures [14][18][19]. For example, it has been reported that the residual stress gradient of the nickel film caused undesired deformation of a moving electrode of a MetalMUMPs[®] tuneable capacitor [14]. The undesired deformation and its effects on the performance of the tuneable capacitor cannot be quantified without information about the residual stress gradient of the nickel film.

In addition to the above properties, a micro bridge mechanism is developed for lifting long silicon nitride beams above the silicon substrate for the determination of the residual stress difference of the two silicon nitride films.

This thesis provides MetalMUMPs[®] users an important reference of the Young's modulus and the residual stress difference of the silicon nitride films, and the Young's modulus and the residual stress gradient of the nickel film for designing, analyzing and optimizing MetalMUMPs[®] devices.

The thesis is organized as follows. The Young's modulus of the silicon nitride films is extracted in Chapter 2. In Chapter 3, the residual stress difference of the two silicon nitride films is determined. The Young's modulus and the residual stress gradient of the nickel film are extracted in Chapter 4. The micro bridge mechanism is described in Chapter 5. The conclusion and recommendations for future work are described in Chapter 6.

Chapter 2 Extraction of the Young's Modulus of the MetalMUMPs[®] Silicon Nitride Films

In this chapter, the Young's modulus of the MetalMUMPs[®] silicon nitride films is measured. Techniques used to measure the Young's modulus of thin films are described in Section 2.1 followed by an explanation of the fabrication of the prototypes used to determine the Young's modulus of the silicon nitride films in Section 2.2. The Young's modulus of the MetalMUMPs[®] silicon nitride films is then experimentally obtained through the following steps. First, the two silicon nitride film thicknesses are measured in Section 2.3. Second, the resonant frequencies of silicon nitride cantilever beam prototypes are measured in Section 2.4. Lastly, in Section 2.5, the Young's modulus of the silicon nitride films is extracted based on the measured resonant frequencies via numerical simulations.

2.1 Techniques to extract the Young's modulus in thin films

Two classes of methods are commonly used for obtaining the Young's modulus of micro fabricated thin films. One is to obtain the Young's modulus based on the strain versus stress behaviour of the thin film or the displacement versus load relation of micro structures made of the thin film [26]-[44]. The other class of methods extracts the Young's modulus based on the measured resonant frequency of a micro structure made of the thin film [45]-[57].

The methods that employ force or pressure to determine the stress versus strain relationship or the displacement versus load relationship of micro structures include microscale tension tests [28]-[33], micro beam [34][35] and bridge tests [36], nanoindentation tests [37][38], bulge tests [39]-[42] and electrostatic pull-in voltage tests [43][44]. For example, for a tensile tester, Figure 2.1 shows the schematic of such a system where the fringe detectors in the figure

detect the reflected laser signal from gold lines deposited on the polysilicon specimen (see Figure 2.2), which act as gauge markers. In this way, the strain in the test subject during the loading can be monitored and determine the Young's modulus of the specimen [26].

Figure 2.1 Schematic of a measurement system for tensile loading [26].

Figure 2.2 Gold lines on the polysilicon specimen [33].

In nanoindentation, a cantilever beam is bent at its free end with a nanoindenter as illustrated in Figure 2.3. The nanoindenter can monitor the force applied and the displacement. Simple beam theory can convert the displacement into strain and the force into stress to obtain the Young's modulus [26].

Figure 2.3 Schematic of a nanoindenter loading a cantilever beam [26].

Another device fabricated from a thin film is a suspended membrane as shown in Figure 2.4 for investigating the stress-strain behaviour. The membrane is exposed to an elevated pressure on one side causing it to “bulge” in the opposite direction. The deflection of the membrane can be measured optically. A load-deflection relationship of the membrane is then used to extract the Young’s modulus of the film [40].

Figure 2.4 Schematic cross-section of a microfabricated membrane [26].

In electrostatic pull-in voltage tests, micro structures such as cantilever beams (see Figure 2.5) are bended by an electrostatic force. The electrostatic force is generated when a voltage is applied between the cantilever beam and an electrode fabricated on the substrate below the beam.

The Young's modulus is obtained from the stress calculated from the force and the strain from the displacement measured by an optical interferometer [26].

Figure 2.5 Cantilever beam being pulled down by the electrostatic force [26].

The advantage of these methods is they provide a direct measurement of the deformation of the thin film. The stress-strain behaviour of the thin film can be analyzed easily since the slope of the stress-strain curve is equal to the Young's modulus [26]. However, these methods are all destructive. Tensile tests and bending tests are relatively easy to analyze but requires specially designed micro structures to be fabricated, complicated equipment setups and extensive specimen preparation. Nanoindentation is simple and rapid and does not require specific micro structures to be fabricated, but requires expensive equipment.

The other class of methods to obtain the Young's modulus of thin films is vibrating the micro structure to find its resonance frequency and then extract the Young's modulus through an analytical model or through numerical simulation [45]-[57]. Micro structures such as cantilever beams, microbridges and lateral resonators are used for the resonance method. Three different excitation methods (photo-thermal, acoustic and mechanical piezoelectric transducers) as shown in Figure 2.6 can be deployed to excite the micro structures. Also, electrostatic comb drives with an alternating current (AC) signal are used to excite lateral resonators (Figure 2.7).

Figure 2.6 Three methods for activating microresonators: a) photothermal, b) acoustic, and c) mechanical [49].

Figure 2.7 SEM photo of a lateral resonator [26].

The resonance method is simple and non-destructive, since the micro structures used for this method operate in the elastic region of the stress-strain curve of the film's material. The cantilever beams can be excited regardless of their deflection after fabrication for low-stress thin films and the small deflection of the cantilever beams has no visible influence on the resonance behaviour of the beams [47]. In this thesis, the resonance method was chosen to determine the Young's modulus of the MetalMUMPs[®] silicon nitride films.

2.2 Silicon nitride prototypes

Single layer silicon nitride cantilever beam prototypes were fabricated using the MetalMUMPs[®] process for the determination of the Young's modulus of the silicon nitride films. The MetalMUMPs[®] process steps involved in the fabrication of the single layer silicon nitride cantilever beams are explained below [13][58]. The terms "OXIDE1", "POLY", and "NITRHOLE" are the masking names given in the MetalMUMPs[®] design handbook [13] and the thicknesses mentioned below are the nominal values [13].

1. An n-type <100> silicon wafer (0.5 mm thick) with a 2 μm thick silicon dioxide isolation layer (Isolation Oxide) is used as the initial substrate. This followed by the deposition of the oxide 1 layer of 0.5 μm thick PSG (Figure 2.8a).

2. The oxide 1 layer is lithographically patterned with an "OXIDE1" mask and the unwanted PSG is removed by wet chemical etching. The remaining oxide 1 layer is used as the sacrificial release layer to define the silicon trench below the silicon nitride cantilever beams (Figure 2.8b).

3. A blanket layer of low-stress silicon nitride (0.35 μm thick) is deposited (Nitride 1) by low pressure chemical vapor deposition (LPCVD) and is immediately followed by a LPCVD polysilicon layer (0.7 μm thick) (Figure 2.8c).

4. Certain areas of the polysilicon layer are lithographically patterned with a "POLY" mask and reactive ion etching (RIE) is used to remove the unwanted polysilicon (Figure 2.8d).

5. A second layer of 0.35 μm thick low-stress LPCVD silicon nitride (Nitride 2) is deposited (Figure 2.8e). Regions of the silicon nitride layer are lithographically patterned with the "NITRHOLE" mask and RIE is performed to remove both the Nitride 2 and Nitride 1 from

the patterned areas. Nitride 1 will remain anywhere the “NITRHOLE” mask is patterned over the polysilicon layer (Figure 2.8f).

6. A second sacrificial Oxide 2 layer of PSG (1.1 μ m thick) is deposited and annealed at 1050°C for 1 hour (Figure 2.8g).

7. A 49% hydrogen fluoride (HF) solution is used to remove the sacrificial layers (Oxide 1 and Oxide 2) and the Isolation Oxide layer over the trench areas (Figure 2.8h).

Figure 2.8 The MetalMUMPs® processing steps to fabricate the single layer silicon nitride cantilever beams [13].

8. A KOH solution is used to create 25 μm deep trenches in the silicon substrate that were defined by the “OXIDE1” and “NITRHOLE” masks. Any exposed polysilicon is also etched away during the KOH etch. Finally, the single layer silicon nitride cantilever beam is formed (Figure 2.8i).

Fifteen loose dies were fabricated by the MetalMUMPs[®] process. Two loose dies are shown in Figure 2.9. The size of each loose die is 10 mm x 10 mm. Figure 2.10 shows the location of some of the fabricated silicon nitride cantilever beams on the loose die. The individual MetalMUMPs[®] film layers of the loose die are illustrated in Figure 2.11 and Figure 2.12 shows a 3D model of the loose die.

Figure 2.9 The fabricated MetalMUMPs[®] loose dies.

Figure 2.10 The MetalMUMPs[®] silicon nitride cantilever beams fabricated on the loose die.

Figure 2.11 3D model of the individual layers of the MetalMUMPs® loose die.

Figure 2.12 3D model of the MetalMUMPs® loose die.

The silicon nitride cantilever beams fabricated using the MetalMUMPs[®] process are shown in Figure 2.13. Two MetalMUMPs[®] loose dies were used to determine the Young's modulus of the silicon nitride films. All the cantilever beams in Figure 2.13 consist of one layer of silicon nitride and have the same width of 15 μm . The lengths of the beams in Figure 2.13 range from 100 μm to 300 μm in increments of 50 μm .

Figure 2.13 Optical microscope image of the MetalMUMPs[®] single layer silicon nitride cantilever beams.

2.3 Film thickness measurements

Film thickness measurements of the silicon nitride and polysilicon films were measured on the two MetalMUMPs[®] loose dies since the thickness of the fabricated films would vary from the nominal values given by the MetalMUMPs[®] design handbook [13]. The polysilicon film was also measured for its thickness since it was used in building numerical simulation models of the single layer silicon nitride cantilever beams. The thicknesses of the Nitride 2, Nitride 1, and polysilicon layers were measured using a scanning white light interferometry (SWLI) 3D optical interferometer (Zygo[®] NewView[™] 6300) [59] as shown in Figure 2.14. The Zygo[®] optical interferometer has a vertical resolution up to 0.1 nm and a lateral resolution of 0.43 μm to 11.6

μm depending on the objective lens used [59]. The MetroPro Films Application of the Zygo® optical interferometer was the software used to measure the thickness of the films [61]. A general procedure to setup the Zygo® optical interferometer is listed in Appendix A and was conducted prior to measuring the thickness of the films. Scan lengths of 5 μm , 10 μm , and 15 μm were used in the measurements. A 20X objective lens was used with the 2X internal magnification of the Zygo® optical interferometer.

Figure 2.14 The Zygo® NewView 6300 SWLI 3D optical interferometer.

The two MetalMUMPs® loose dies included five specifically designed trenches (named Poly trench) used to measure the thickness of the Nitride 2 layer. Table 2.1 lists the dimensions of those trenches. A technical drawing of the trench is listed in Appendix B. The specifically designed trench is formed by patterning the polysilicon layer (defined by the “POLY” mask) on top of the Nitride 1 layer, and lithographically cutting out the Nitride 2 layer with two rectangular holes (defined by the “NITRHOLE” mask) such that the polysilicon layer is exposed during the KOH etch in the MetalMUMPs® process as shown in Figure 2.15.

Using the MetroPro Films Application, the central region of each of the five trenches (Figure 2.16) was scanned for its surface profile as shown in Figure 2.17a. “Poly” slice lines were drawn within the surface profile of the trench (two slice lines are shown in Figure 2.17a).

The “Poly” slice line is a type of slice line in MetroPro that allows the user to draw multiple lines which are distinctively and chronologically labelled by the software. The data points of the profile plot of the slice lines (two are shown in Figure 2.17b) were saved in an “.xls” (Microsoft Excel) file. For each slice line, the Nitride 2 thickness was obtained by taking the average of the measured data points of the top surface of the Nitride 2 layer (Figure 2.18, point A) minus the average of the measured data points of the top surface of the Nitride 1 layer (Figure 2.18, point B) in Microsoft Excel. Four slice lines were used in each of the five trenches, making a total of 20 measurements on each loose die for the Nitride 2 layer.

Table 2.1 Trench dimensions.

Poly Trench No.	NITRHOLE Width (μm)	NITRHOLE Length (μm)
1	180	430
2	160	410
3	140	390
4	120	370
5	100	350

Figure 2.15 The trench layout.

Figure 2.16 Optical microscope image of the central region of the Poly trench for measuring the Nitride 2 thickness.

a) Surface profile with slice lines

b) Profile plot of the two slice lines

Figure 2.17 Measuring the Nitride 2 thickness with the Poly trench. a) Surface profile with slice lines and b) Profile plot of the two slice lines.

Figure 2.18 Side view of the Poly trench.

The thickness of the Nitride 1 layer was determined by subtracting the measured Nitride 2 thickness from the total thickness of two combined silicon nitride layers. At least three 50 μm wide with lengths ranging from 500 μm to 550 μm of silicon nitride bi-layered (two layers) cantilever beams sticking to the surface of the substrate trench (i.e., the surface of the trench in the silicon substrate) (see Figure 2.19) were used to measure the thickness of the two combined silicon nitride layers. A layout drawing defined by the MetalMUMPs[®] mask layers to fabricate the silicon nitride bi-layered cantilever beams is listed in Appendix B and the MetalMUMPs[®] process steps involved in the fabrication of the silicon nitride bi-layered cantilever beams are described in Section 3.3. Possible causes for the beams to stick to the surface of the substrate trench are due to the centripetal forces generated during the rinsing and drying stages of the

micro fabrication process or the external forces generated by mishandling of the loose dies during packaging and shipment [62].

Figure 2.19 a) SEM image and b) optical microscope image of the silicon nitride bi-layered beams sticking to the surface of the substrate trench.

Using the MetroPro Films Application, the 50 μm wide silicon nitride bi-layered beams sticking to the surface of the substrate trench were scanned for their surface profiles. “Poly” slice lines were drawn across the width of the beams within the surface profile (ten slice lines are shown in Figure 2.20a) and the data points of the profile plot of the slice lines were saved in an “.xls” file. For each slice line, the thickness of the two combined silicon nitride layers was obtained by subtracting the average of two data points on the surface of the substrate trench near the beam (Figure 2.20b, point C) from the average of the measured data points of the top surface of the Nitride 2 layer (Figure 2.20b, point D) in Microsoft Excel. A total of twenty slice lines were used to measure the thickness of the two combined silicon nitride layers on each loose die.

Figure 2.20 Measuring the thickness of the silicon nitride bi-layer beams on the substrate. a) Surface profile with slice lines and b) Side view of the beam on the substrate trench.

The thickness of the Nitride 1 layer was also obtained by measuring at least more than five 15 μm wide single layer silicon nitride cantilever beams sticking to the surface of the substrate trench. A layout drawing defined by the MetalMUMPs[®] mask layers to fabricate the single layer silicon nitride cantilever beams is listed in Appendix B. Figure 2.21 shows the 15 μm wide single layer cantilever beams sticking to the surface of the substrate trench with one end attached to a micro bridge mechanism (see Chapter 5). The single layer silicon nitride cantilever beams shown in Figure 2.21 have lengths longer than 350 μm .

The 15 μm wide single layer silicon nitride beams sticking to the surface of the substrate trench were scanned for their surface profiles using the MetroPro Films Application. “Poly” slice lines were drawn across the width of the beams within the surface profile (ten slice lines are shown in Figure 2.22a) and the data points of the profile plot of the slice lines were saved in an “.xls” file. For each slice line, the Nitride 1 thickness was determined by subtracting the average of two data points on the surface of the substrate trench near the beam (Figure 2.22b, point E) from the average of the measured data points of the top surface of the Nitride 1 layer (Figure

2.22b, point F) in Microsoft Excel. A total of twenty slice lines were used to measure the Nitride 1 thickness only on loose die 2.

Figure 2.21 Optical microscope image of the single layer silicon nitride beams sticking to the surface of the substrate trench.

a) Surface profile with slice lines

b) Side view

Figure 2.22 Measuring the thickness of the single layer silicon nitride beams on the substrate a) Surface profile with slice lines and b) Side view of the beam on the substrate trench.

At least three nitride-polysilicon-nitride cantilever beams sticking to the surface of the substrate trench were used to measure the thickness of the polysilicon layer as shown in Figure 2.23. The beams in Figure 2.23 have a width of 40 μm for the silicon nitride layers, a width of 20

μm for the polysilicon layer and lengths ranging from 160 μm to 560 μm . A layout drawing defined by the MetalMUMPs[®] mask layers to fabricate the nitride-polysilicon-nitride cantilever beams is listed in Appendix B.

The nitride-polysilicon-nitride cantilever beams sticking to the surface of the substrate trench were scanned for their surface profiles using the MetroPro Films Application. “Poly” slice lines were drawn across the width of the beams within the surface profile (ten slice lines are shown in Figure 2.24a) and the data points of the profile plot of the slice lines were saved in an “.xls” file. For each slice line, the polysilicon thickness was determined by subtracting the average of the measured data points of the top surface of the Nitride 2 layer which is on top of the Nitride 1 layer (Figure 2.24b, point G) from the average of the measured data points of the top surface of the Nitride 2 layer which is on top of the polysilicon layer (Figure 2.24b, point H) in Microsoft Excel. A total of twenty slice lines were used to measure the polysilicon thickness on each loose die.

Figure 2.23 SEM image of the nitride-polysilicon-nitride cantilever beams sticking to the surface of the substrate trench.

a) Surface profile with slice lines

a) Side view

Figure 2.24 Measuring the thickness of the nitride-polysilicon-nitride cantilever beams on the substrate. a) Surface profile with slice lines and b) Side view of the beam on the substrate trench.

Finally, the measured average thickness and standard deviation of the Nitride 2 (h_2) layer, the two combined silicon nitride layers (h_{total}), the Nitride 1 (h_1) layer and the polysilicon layer are summarized in Table 2.2 for loose die 1 and loose die 2. Equation (2.1) was used to find the population standard deviation, σ_p , for each film thickness of each loose die. x_i represents each data point value, $\bar{x}$ is the mean of the corresponding population, and the number of data points in the population is N .

$$\sigma_p = \sqrt{\frac{\sum_{i=1}^N (x_i - \bar{x})^2}{N}} \quad (2.1)$$

All the thickness measurements of the Nitride 2 layer, two combined silicon nitride layers, Nitride 1 layer (measured on the surface of the substrate trench) and polysilicon layer are listed in Appendix C for loose die 1 and loose die 2.

Table 2.2 Measured thicknesses of the silicon nitride and polysilicon layers.

Film	Thickness (μm)	
	Loose Die 1	Loose Die 2
Nitride 2 (h_2)	0.250 ± 0.002	0.258 ± 0.002
Combined Nitride (h_{total})	0.571 ± 0.006	0.584 ± 0.006
Nitride 1 (h_{1S}) by subtraction	0.321 ± 0.004	0.326 ± 0.004
Nitride 1 (h_1) on substrate	n/a	0.323 ± 0.004
Polysilicon	0.691 ± 0.010	0.693 ± 0.014

2.4 Resonant frequency measurements

2.4.1 The piezoelectric transducer

Piezoelectric transducers were used to excite the single layer silicon nitride cantilever beams for their resonant frequencies. Piezoelectric transducers were used because MetalMUMPs[®] silicon nitride is a non-conductive material and thus electrostatic force actuation cannot be used to excite the beams. Another reason to use piezoelectric transducers was to avoid the shift of the resonant frequency of the beams caused by electromechanical coupling [47] and the effect of spring softening of the beams associated with electrostatic excitation [63][64].

The piezoelectric transducer includes a steel chair-like base, a Lexan[™] (plastic) insulator, and a 13 mm x 13 mm x 1 mm piezoelectric ceramic (APC International, Ltd.) as shown in Figure 2.25. Technical drawings of the steel chair-like base and Lexan[™] insulator are listed in Appendix B. The Lexan[™] insulator was glued to the steel chair-like base using LOCTITE[®] epoxy (E-20HP Hysol, part no. 29314) and then a vice was used to clamp the plastic insulator to the steel base. The plastic insulator was clamped to the steel base for 24 hours to allow the epoxy to cure properly. Afterwards, a small electrical wire was soldered to the bottom surface of the piezoelectric ceramic in its center and was routed through the hole of the plastic insulator and the steel base. Then epoxy was applied around the wire to permanently secure it to the steel base (see

Figure 2.25a) and the piezoelectric ceramic was glued to the plastic insulator using the epoxy and was clamped with the vice for 24 hours. Because the vice has a hard metallic surface, a piece of plastic was placed between the vice and the piezoelectric ceramic to avoid damaging the piezoelectric ceramic. The loose die was bonded on top of the ceramic using instant KRAZY[®] glue. Careful considering was taken not to apply too much instant KRAZY[®] glue to prevent the glue flowing into the micro structures on the loose die. Lastly, a second small electrical wire was soldered to one corner of the top surface of the piezoelectric ceramic and then epoxy was applied over the wire to permanently secure it to the plastic insulator (see Figure 2.25b).

Figure 2.25 The steel chair piezoelectric transducer configuration: a) Bottom view, b) Top view.

2.4.2 Experimental setup for frequency measurement

The experimental setup is illustrated in Figure 2.26. The piezoelectric transducer was secured under the Zygo[®] optical interferometer on the stage with double sided tape as shown in Figure 2.27. The function generator used is a Tegan Pragmatic model 2416A and the high-voltage amplifier used is a Tegan Model 2350. The high-voltage amplifier increases the output voltage from the function generator by 25X. The electrical connections of the setup are

illustrated in Figure 2.28. The Zygo[®] electronic enclosure was connected to the “SYNC OUT” port of the function generator using a male-male BNC coaxial cable (RG58C/U) as shown in Figure 2.29 and Figure 2.30. The function generator was connected using a USB interface connector (National Instruments GPIB-USB-HS) to the computer workstation as shown Figure 2.31. The voltage amplifier was connected to the function generator using a male-male BNC coaxial cable (RG58C/U). The voltage amplifier was connected to the positive and negative electrical wires of the piezoelectric ceramic of the piezoelectric transducer using a female-male BNC cable connected to a male-splitter BNC cable (has positive and negative wire grippers) with a BNC coupler (joins two BNC male connectors). The positive wire gripper of the male-splitter BNC cable was connected to the positive (bottom) wire of the piezoelectric ceramic and the negative wire gripper of the male-splitter BNC cable was connected to the negative (top) wire of the piezoelectric ceramic as shown in Figure 2.32.

Figure 2.26 Experimental setup to measure the resonant frequencies of the silicon nitride cantilever beams.

Figure 2.27 The piezoelectric transducer under the Zygo[®] optical interferometer.

Figure 2.28 Electrical schematic of the experimental setup.

Figure 2.29 Connection from the Zygo® electronic enclosure to the function generator.

Figure 2.30 Close up of the connections at the function generator and voltage amplifier.

Figure 2.31 USB interface connection from the function generator to the computer workstation.

Figure 2.32 Connections between the voltage amplifier and the piezoelectric ceramic.

2.4.3 Resonant frequency measurements

The resonance frequencies of at least two single layer silicon nitride cantilever beams of the same length were measured. The beams with lengths of 100 μm and 150 μm were measured for their first mode resonant frequencies. The beams with lengths of 200 μm , 250 μm , and 300 μm were measured for their second mode resonant frequencies. The above modes were chosen specifically due to the first mode resonant frequencies for the longer beams were too low for the piezoelectric transducer. The setup of the Zygo[®] optical interferometer was conducted using the general procedure in Appendix A. The MetroPro Dynamics Application of the Zygo[®] optical interferometer was used in the resonant frequency measurements [65]. The resonant frequency of each single layer silicon nitride cantilever beam was measured by the following procedure.

First, the beam was scanned with a manual sweep. The beam was excited by manually changing the frequency on the function generator of the sinusoidal signal applied to the piezoelectric transducer and then monitoring the interference fringes on the beam (see Figure 2.33) through the camera of the Zygo[®] optical interferometer to roughly estimate the frequency scanning range for a coarse sweep of the beam. A frequency increment of 1000 Hz and voltage amplitudes of 0.5 V up to 5 V (depending on the length of the beam) were used in the manual sweep. When a change in the fringes on the beam was observed, the frequency from the function generator was then used to calculate the frequency scanning range for the coarse sweep of the beam. A ± 2000 Hz up to ± 3000 Hz was used for the frequency scanning range of the coarse sweep of the beam. For example, for one of the 100 μm long beams, a frequency of 42 kHz was obtained from the manual sweep of the beam and a frequency scanning range of 39 kHz to 45 kHz was calculated for the coarse sweep of the beam.

Figure 2.33 Interference fringes on the beam.

Second, the beam was scanned with two frequency sweeps: a coarse sweep and a fine sweep, by using the Zygo[®] optical interferometer to determine the resonant frequency of the beam. When excited by the piezoelectric transducer, the beam oscillates and the surface profile is measured at every phase of the driving signal by the optical interferometer. The phase is expressed in degrees with respect to the driving signal applied to the piezoelectric transducer. The oscillation displacement of the beam tip is measured by the optical interferometer at every phase during the frequency sweep and plots every measurement into a chart in the MetroPro Dynamics Application. The chart is a plot of the frequency response curve of the beam. The curve is then measured for its largest peak to valley displacement. The resonant frequency of the beam is determined by the frequency used to generate the largest peak to valley displacement in the frequency response curve of the beam.

The coarse sweep was conducted to determine the frequency scanning range for the fine sweep of the beam and the fine sweep was conducted to determine the resonant frequency of the beam. A frequency increment of 500 Hz was used for the coarse sweep and a frequency increment of 100 Hz was used for the fine sweep. The frequency that generated the largest peak

to valley displacement in the frequency response curve of the coarse sweep of the beam was used to determine the frequency scanning range for the fine sweep of the beam. A ± 300 Hz up to ± 1000 Hz was used for the frequency scanning range of the fine sweep of the beam. In the MetroPro Dynamics Application, the following settings were utilized: 1) The 20X objective lens was used with the 2X internal magnification of the scope; 2) A circular mask was applied near the free end of the beam (Figure 2.34); 3) A scan length of $5\text{ }\mu\text{m}$ was used in the measurements; 4) A sine waveform was used; 5) Depending on the length of the beam, the applied voltage amplitude ranged from 0.5 V to 5 V; 6) The voltage offset was set to 0 V; 7) The sweep mode was set to “frequency & phase”; 8) The start and end phase delay was set to 0° and 360° , respectively; and 9) The phase delay increment was set to 45° .

Figure 2.34 Circular mask applied to the tip of the cantilever beam.

Figure 2.35 shows the measured frequency response curve of a $150\text{ }\mu\text{m}$ long single layer silicon nitride beam (18200 Hz to 19400 Hz with an increment of 100 Hz). The curve in Figure 2.35 was measured for its largest peak to valley displacement and 18800 Hz was determined as the first mode resonant frequency for the $150\text{ }\mu\text{m}$ single layer silicon nitride beam. Similarly, Figure 2.36 shows the measured frequency response curve of a $250\text{ }\mu\text{m}$ long single layer silicon

nitride beam (42000 Hz to 44000 Hz with an increment of 100 Hz) and a second mode resonant frequency of 43100 Hz was determined for the beam. The lowest possible frequency increment for the fine sweep was 100 Hz. Changing the frequency increment to a smaller frequency (e.g., 50 Hz) did not significantly change the frequency response curve of the beam during the measurement.

Figure 2.35 Frequency response curve for a 150 μm long single layer silicon nitride cantilever beam.

Figure 2.36 Frequency response curve for a 250 μm long single layer silicon nitride cantilever beam.

Lastly, the vibration mode of the beam was verified by measuring the deflection profile of the beam when it oscillates at its measured resonant frequency, which is obtained by subtracting the beam's surface profile measured when it is at rest from the beam's surface profile measured when it oscillates at every phase of the driving signal. The applied voltage amplitude was set to the voltage amplitude that was used to determine the resonant frequency of the beam.

The driver frequency was set to the resonant frequency of the beam. The sweep mode was set to “phase”. Figure 2.37 and Figure 2.38 illustrates the deflection profiles of a 150 μm long and a 250 μm long single layer silicon nitride beams oscillating at their resonant frequencies, respectively. The figures show when the beams are at rest and when the beams are deflected at different phases. The first vibration mode of the beam is verified when the beam oscillates in the first mode shape (flips up and down). The second vibration mode of the beam is verified when the beam oscillates in the second mode shape (a wave like pattern with one stationary node).

The measured resonant frequencies of all the single layer silicon nitride beams are shown in Figure 2.39. The resonant frequency measurements of each single layer silicon nitride cantilever beam are listed in Appendix C.

Figure 2.37 Deflection profiles of a 150 μm single layer silicon nitride beam, a) at rest, and oscillating at its first mode resonant frequency when the phase is at b) 0°, c) 180°, and d) 360°.

Figure 2.38 Deflection profiles of a 250 μm single layer silicon nitride beam, a) at rest, and oscillating at its second mode resonance frequency when the phase is at b) 0°, c) 180°, and d) 360°.

Figure 2.39 Measured resonance frequencies of all the single layer silicon nitride cantilever beams.

2.5 Young's modulus extraction for the silicon nitride films

The natural frequency of an undamped cantilever beam is given by [66][67]:

$$f_n = \frac{\alpha_n^2}{2\pi L^2} \sqrt{\frac{\bar{E}I}{\rho A}} \quad (2.2)$$

where L is the length of the beam, I is the second moment of inertia of the beam cross-section, A is the beam cross-sectional area, $\bar{E}$ and ρ are the effective Young's modulus and the mass density respectively of the material. α_n is the eigenvalue, where n is an integer that describes the resonance mode number; for the first mode ($n=1$), $\alpha_1 = 1.87510407$ and the second mode ($n=2$), $\alpha_2 = 4.69409113$ [67]. The effective Young's modulus, $\bar{E}$, is dependent on the beam width [44][47][68]:

$$\bar{E} = \begin{cases} E & b < 5h \\ E/(1-\nu^2) & b \geq 5h \end{cases} \quad (2.3)$$

where ν is Poisson's ratio, b and h are the width and thickness of the cantilever beam, respectively. The cantilever beams used in this analysis have widths of more than five times larger than the thickness, hence, $E/(1-\nu^2)$ was used to account for plane-strain conditions [44][47]. Taking the moment of inertia for a rectangular cross-section as $I = bh^3/12$, the area as $A = bh$ and the effective modulus as $\bar{E} = E/(1-\nu^2)$, equation (2.2) simplifies to [47][49]:

$$f_n = \frac{\alpha_n^2 h}{4\pi L^2} \sqrt{\frac{E}{3\rho(1-\nu^2)}} \quad (2.4)$$

Rearranging equation (2.4) for the Young's modulus, E , gives [47][49]:

$$E = \frac{48\pi^2 \rho L^4}{\alpha_n^4 h^2} (1 - \nu^2) f_n^2 \quad (2.5)$$

Thus, the Young's modulus is calculated by equation (2.5) for a given resonance frequency, cantilever beam length, mass density, Poisson's ratio, eigenvalue α and beam thickness.

The calculations of the Young's modulus of the silicon nitride film via equation (2.5) for each beam length that was measured for its resonance frequency are summarized in Table 2.3. These calculations used the resonance frequencies from Figure 2.39, the measured Nitride 1 thicknesses from Table 2.2 (h_{1S} for loose die 1 and h_1 for loose die 2), a Poisson's ratio, ν , of 0.23 [24], and a mass density, ρ , of 3000 kg/m³ [48].

Table 2.3 The Young's modulus of silicon nitride calculated via equation (2.5).

Beam Length (μm)	Young's modulus, E (GPa)
100	183.0
150	182.4
200	190.1
250	193.3
300	194.4
Average	188.7

An average Young's modulus of 188.7 GPa from Table 2.3 is obtained for the silicon nitride film. However, the values calculated by equation (2.5) do not consider the effects of the "shelf" boundary condition. The silicon nitride beams were fabricated with a shelf as indicated in Figure 2.13. The shelf is formed due to the fabrication steps in the MetalMUMPs[®] process in order to create the substrate trench below the cantilever beams [13]. The shelf creates a different boundary condition. As shown in Figure 2.40, the shelf provides a more flexible boundary condition than the ideal fixed-free cantilever boundary condition (see Figure 2.41), which is assumed by the analytical equation. Thus, numerical simulations of the single layer silicon

nitride cantilever beams were conducted to extract the Young's modulus of the MetalMUMPs® silicon nitride film to include the effect of the shelf boundary condition.

Figure 2.40 The shelf boundary condition.

Figure 2.41 The ideal boundary condition for a fixed-free cantilever beam.

Numerical simulations were conducted to extract the Young's modulus of the MetalMUMPs® silicon nitride films since the analytical equations cannot account for the effect of the shelf boundary condition of the silicon nitride beams which were used to measure the resonant frequencies. Numerical simulations have been used to extract the Young's modulus of thin film materials based on the measured resonant frequencies of cantilever beams [55]-[57].

The numerical simulations were conducted using the commercial software CoventorWare™ Version 2008.010 [69] to extract the Young's modulus of the silicon nitride film. 3D beam models of each beam length were built using the foundry MetalMUMPs® process included in CoventorWare™ [69] and the measured thicknesses from Table 2.2 (h_{1S} for loose die 1 and h_1 for loose die 2). The beam models have an orthogonal geometry and were thus meshed using 27-node Manhattan Bricks (hexahedral (brick) elements). Manhattan Bricks meshes with a size (X, Y, Z) of $5\text{ }\mu\text{m} \times 5\text{ }\mu\text{m} \times Z\text{ }\mu\text{m}$, $3\text{ }\mu\text{m} \times 3\text{ }\mu\text{m} \times Z\text{ }\mu\text{m}$, and $1.5\text{ }\mu\text{m} \times 1.5\text{ }\mu\text{m} \times Z\text{ }\mu\text{m}$ were tested (the Z dimension was the thickness of the film in the beam model and was automatically determined by the software) and it was found that a $1.5\text{ }\mu\text{m} \times 1.5\text{ }\mu\text{m} \times Z\text{ }\mu\text{m}$ Manhattan Bricks mesh was sufficient to obtain accurate results. The 3D model of a $15\text{ }\mu\text{m} \times 200\text{ }\mu\text{m}$ single layer silicon nitride cantilever beam is illustrated in Figure 2.42 with the shelf boundary included. Each beam model was anchored (fixed) as shown in Figure 2.42. A Poisson's ratio, ν , of 0.23 [24] and mass density, ρ , of 3000 kg/m^3 [48] for the silicon nitride were used in the simulations. All the simulations used the lanczos mode solution method.

Figure 2.42 The $15\text{ }\mu\text{m} \times 200\text{ }\mu\text{m}$ model of the single layer silicon nitride cantilever beam in CoventorWare™.

Each beam model was simulated by varying the Young's modulus of the silicon nitride until the simulated resonant frequency matched the measured resonant frequency (from Figure 2.39) with an accuracy of ± 100 Hz. Thus, the extracted Young's modulus of the MetalMUMPs[®] silicon nitride films is listed in Appendix C and is shown in Figure 2.43 for all the beams with an average and standard deviation (σ_p via equation (2.1)) of $209 \text{ GPa} \pm 3.9 \text{ GPa}$.

Figure 2.43 Extracted values of the Young's modulus for the MetalMUMPs[®] silicon nitride films.

Chapter 3 Determination of the Residual Stress Difference of the Two MetalMUMPs[®] Silicon Nitride Films

In MetalMUMPs[®], the two silicon nitride films are used for the mechanical connection and electrical insulation for suspended micro structures made of the nickel film [16][19][20]. The two silicon nitride films are either bonded together as a bi-layered structure or they sandwich the polysilicon film to form a tri-layered structure to suspend MetalMUMPs[®] devices. The two MetalMUMPs[®] silicon nitride films have different residual stresses due to different thermal-mechanical interactions between each film and its substrate, different deposited film thicknesses, and the different thermal cycling that each film goes through in the fabrication process [70]-[74]. A residual stress difference of the two silicon nitride films causes undesired deformations and deteriorates the performance of MetalMUMPs[®] devices, which are suspended by silicon nitride bi-layer structures. Thus far, the residual stress difference of the two MetalMUMPs[®] silicon nitride films is not available.

In this chapter, a method is proposed, which uses the deformations along the width of bi-layered cantilever beams, to determine the residual stress difference of the two MetalMUMPs[®] silicon nitride films. First, the techniques of determining the residual stresses in thin films are introduced in Section 3.1. Second, the factors that cause the residual stress difference are discussed in Section 3.2. Third, the fabrication of the prototypes used to determine the residual stress difference of the two silicon nitride films are described in Section 3.3. Fourth, an analytical model relating the residual stress difference of the two silicon nitride films to the radius of curvature along the width of a silicon nitride bi-layer cantilever beam is introduced in Section 3.4. Fifth, in Section 3.5, the silicon nitride bi-layered cantilever beam prototypes are measured for

their radii of curvature along the width using the Zygo[®] optical interferometer. Sixth, the residual stress difference of the two silicon nitride films is determined in Section 3.6 using the measured radius of curvature results and the derived equation from the analytical model of Section 3.4. Lastly, in Section 3.7, all the bi-layered cantilever beam prototypes are simulated for their radii of curvature along the width and compared to the measured radius of curvature results from Section 3.5 to verify the extracted results of the residual stress difference.

3.1 Techniques to determine the residual stress in thin films

Residual stress in MEMs is known as the stress left behind in the thin film after micro fabrication without the presence of external forces or thermal gradients [74]. In thin films, there are two types of residual stresses: thermal and intrinsic. Thermal residual stresses are generated when two materials having different thermal-mechanical properties, e.g., coefficient of thermal expansion, are joined together and induce microscope strain as the temperature changes in the materials [74][75]. Intrinsic residual stresses are stresses that are “grown” within the deposited material due to the accumulating effect of changes to the microstructures, i.e., changes to the normal spacing between atoms or molecules, to generate microscope strain during the deposition of the material [74]-[76].

The total intrinsic residual stress can be approximated by superimposing a residual mean (average) stress and a residual stress gradient [77]. There are two types of intrinsic residual stresses in thin films: tensile and compressive [75]. Tensile residual stress results in the shrinkage of thin films due to the attractive forces between atoms in the material across microvoids, e.g., voids in the grain boundaries and atomic vacancies in the material, which are formed during the deposition of the material [75]. Compressive residual stress results in the expansion or elongation of thin films due to the filling of excess vacancies by atoms or molecules in the

material or when the atoms in the material are packed more tightly during deposition of the material [74][75]. A non-uniform residual stress over the cross-section of a thin film results in a residual stress gradient. The residual stress gradient is defined as the stress that varies across the thickness from the bottom surface to the top surface of the thin film [75]. As a consequence, thin film structures would bend, such as a micro cantilever beam, upward with a positive stress gradient, or downward with a negative stress gradient [68].

In general, the deformations of the thin film due to the total intrinsic residual stress can be explained by the stresses initially formed during the deposition of the material (i.e., the thin metal film on the substrate) [77][78]. Figure 3.1a depicts the thin metal film on the substrate. The initially formed stress which is held within the material layer tries to release itself [77]. However, the metal is “bonded” to the substrate, which inhibits the metallic film from deforming freely. The sacrificial layer and a portion of the substrate are then removed (Figure 3.1b). Afterwards, the total residual (initial) stresses in the thin film are released and the thin film is allowed to deform into its final state as shown in Figure 3.1c [77][78].

Figure 3.1 Thin film deformed by the total intrinsic residual stresses. [77].

Thin films affected by the residual stress causes undesired deformations in the micro structures of MEMS devices or change the effective stiffness of the micro structures [74]. For example, a micro machined structure of a micro actuator affected by the residual stress gradient

is shown in Figure 3.2. However, the residual stress can be intended in the design of MEMS devices by using the residual stress gradient to deform micro structures for assembling out-of-plane micro components as shown in Figure 3.3 [79].

Figure 3.2 SEM photo of a portion of a microactuator deformed by the residual stress gradient [26].

Figure 3.3 SEM photo of several raised structures assembled using simple lifters induced by the residual stress gradient [79].

The most common technique to determine the residual mean stress or the residual stress gradient in thin films involve measuring the deformation of pre-deformed micro structures or wafers made of the thin film material. The other techniques mentioned in Section 2.1, such as nanoindentation and bulge testing, also determine the residual stresses in thin films. Examples of pre-deformed micro structures measured for their deformations include cantilever beams

[75][77]-[82], micro strain gauges [82][83], micro bridges [84] and micro wafers [74][85]. All these pre-deformed micro structures are deformed after the residual stresses are released.

Examples of micro cantilever beams deformed by the residual stress gradient are shown in Figure 3.4. The tip deflection or curvature of the cantilever beams is measured and a mechanical model is used to relate the deformation to the residual stresses in the beam [78]. Micro strain gauges as shown Figure 3.5 use Vernier scales to obtain the residual strain (lateral displacement) and then the internal residual stress in the gauge [82]. The Vernier scales are read using optical microscopy [26]. Measuring the deformation profile of a released bi-layered cantilever beam (see Figure 3.6) along its length is another pre-deformed micro structure example that has been widely used to determine the residual stresses in thin films [86]-[93].

Figure 3.4 SEM photo of micro cantilever beams deformed by the residual stress gradient [78].

Figure 3.5 a) Vernier scale micro strain gauge, b) Close-up of the Vernier scale [26].

Figure 3.6 SEM photo of a deformed bi-layer cantilever beam [87].

The advantage of using pre-deformed micro structures is that different types of a large array of test structures with a variety of geometries and the simplicity to achieve in-plane structural complexity can be fabricated for the measurement of their deformations. These micro structures can be integrated with active devices, which can accurately measure the residual strain, and then the residual stress by examining the response of the structure [27]. However, a drawback of using pre-deformed micro structures is the limitation of the optical resolution of the measuring devices used to measure the deformation of pre-deformed micro structures visually or the limited resolution of the micro fabricated Vernier scales [83].

3.2 Factors that cause the residual stress difference

The two MetalMUMPs[®] silicon nitride films have different residual stresses due to different thermal-mechanical interactions between each film and its substrate underneath or other deposited films, different deposited film thicknesses, and the different thermal cycling that each film goes through in the fabrication process [70]-[74]. The following lists the processing conditions that the silicon nitride films experiences in the MetalMUMPs[®] process:

- Deposition of Nitride 1, typical deposition temperature and pressure: 700-900 °C and 200-500 mtorr [70][94]

- Deposition of polysilicon, typical deposition temperature and pressure: 580-650 °C and 100-400 mtorr [71][94] (Nitride 1 experiences thermo-mechanical interactions with polysilicon and a temperature difference)
- Etching of polysilicon by RIE at room temperature (Nitride 1 experiences a temperature difference)
- Deposition of Nitride 2, same deposition temperature and pressure as Nitride 1 (Nitride 1 experiences a thermal cycle and thermo-mechanical interactions with Nitride 2)
- Etching of Nitride 1 and Nitride 2 by RIE at room temperature (Nitride 1 and Nitride 2 experience a thermal cycle)
- Deposition of Oxide 2 (Nitride 1 and Nitride 2 experience a thermal cycle)
- All the deposited films are annealed at 1050°C for 1 hour (Nitride 1 and Nitride 2 experience a thermal cycle)
- Etching of Oxide 2, Oxide 1 and Isolation Oxide by HF solution
- Etching of the silicon substrate to form the trench by KOH solution

The above list shows that Nitride 1 and Nitride 2 go through different processing conditions and thermal cycles, which are the major factors that cause the residual stress difference in the two silicon nitride films.

3.3 Silicon nitride bi-layered prototypes

Silicon nitride bi-layered cantilever beams were fabricated using the MetalMUMPs® process to determine the residual stress difference of the two silicon nitride films. Similar to

Section 2.2, the MetalMUMPs[®] process steps involved in the fabrication of the silicon nitride bi-layered cantilever beams are explained below [13][58]:

1. An n-type <100> silicon wafer (0.5 mm thick) with a 2 μm thick silicon dioxide isolation layer (Isolation Oxide) is used as the initial substrate. This followed by the deposition of the oxide 1 layer of 0.5 μm thick PSG (Figure 3.7a).
2. The oxide 1 layer is lithographically patterned with an “OXIDE1” mask and the unwanted PSG is removed by wet chemical etching. The remaining oxide 1 layer is used as the sacrificial release layer to define the silicon trench below the silicon nitride bi-layered cantilever beams (Figure 3.7b).
3. A blanket layer of 0.35 μm thick low-stress LPCVD silicon nitride (Nitride 1) is deposited and is immediately followed by a LPCVD polysilicon layer (0.7 μm thick) (Figure 3.7c).
4. The polysilicon layer is lithographically patterned with the “POLY” mask and RIE is used to remove the unwanted polysilicon (Figure 3.7d).
5. A second layer of 0.35 μm thick low-stress LPCVD silicon nitride (Nitride 2) is deposited (Figure 3.7e). Regions of the silicon nitride layer are lithographically patterned with the “NITRHOLE” mask and RIE is performed to remove both the Nitride 2 and Nitride 1 from the patterned areas (Figure 3.7f).
6. A second sacrificial Oxide 2 layer of PSG (1.1 μm thick) is deposited and annealed at 1050°C for 1 hour (Figure 3.7g).
7. A 49% HF solution is used to remove the sacrificial layers (Oxide 1 and Oxide 2) and the Isolation Oxide layer over the trench areas (Figure 3.7h).

8. A KOH solution is used to create 25 μm deep trenches in the silicon substrate that were defined by the “OXIDE1” and “NITRHOLE” masks. Finally, the silicon nitride bi-layered cantilever beam is formed (Figure 3.7i).

Figure 3.7 The MetalMUMPs® processing steps to fabricate the silicon nitride bi-layered cantilever beams [13].

3.4 Analytical model for the residual stress difference

In a single layer cantilever beam with a zero residual stress gradient across the thickness, the beam remains flat after being released. Similarly, for a bi-layered cantilever beam with a zero

residual stress gradient in each film, the same outcome occurs if the residual mean stresses in both films are the same. However, different residual mean stresses in the two layers of a bi-layered cantilever beam causes deformation when the beam is released, e.g., the beam curves up or down [74][88]. In this section, an analytical equation relating the residual stress difference of the silicon nitride two films to the radius of curvature along the width of a silicon nitride bi-layered cantilever beam is derived.

Using the Zygo[®] optical interferometer, scanned surface profiles of the fabricated MetalMUMPs[®] silicon nitride bi-layered cantilever beams are shown in Figure 3.8 as a 3D model. The beams have a width of 25 μm and lengths ranging from 200 μm to 550 μm . A surface deflection profile of a 25 μm x 250 μm silicon nitride bi-layered cantilever beam as indicated in Figure 3.8a along its length is shown in Figure 3.9. From Figure 3.8 and Figure 3.9, the beam bends downward at the fixed boundary of the beam. The downward bending of the beam at the fixed boundary might be caused by external forces such as the centripetal forces generated in the rinsing and drying stages of the micro fabrication process, which induces plastic deformation at the fixed boundary of the beam. Hence, the deformation along the whole beam length cannot be easily used to determine the residual stress difference of the two silicon nitride films since it is affected by the plastic deformation at the fixed boundary of the beam.

A surface deflection profile along the width of the 25 μm x 250 μm silicon nitride bi-layered cantilever beam at three locations on the beam is shown in Figure 3.10. The three locations were measured in the central region, i.e., far from the fixed and free boundaries, of the beam and are indicated in Figure 3.11. From Figure 3.10, the small deformations along the width at the three locations of the beam have a curvature shape and no plastic deformation is observed. Hence, the residual stress difference in the two silicon nitride films can be easily extracted based

on the measured radius of curvature along the width of the deformed bi-layered beam. Based on these observations, the deformations along the beam width that are located in the central region of the beam can be considered as free beams that are not affected by any external forces or by the beam boundary conditions. This is because the deformation along the beam width in the central region along the beam length is uniform and thus any slice along the beam width taken out from the central region is free, i.e., it is not restrained by its neighbouring slices. Therefore, the deformations (or radii of curvature) along the width of the silicon nitride bi-layered cantilever beams are used to determine the residual stress difference of the two silicon nitride films.

Figure 3.8 3D model of the scanned surface profiles of the 25 μm wide silicon nitride bi-layered cantilever beams. a) Oblique view and b) In-plane view.

Figure 3.9 Profile plot of the 25 μm x 250 μm silicon nitride bi-layered beam along its length.

Figure 3.10 Profile plot of the three locations measured along the width of the 25 μm x 250 μm silicon nitride bi-layered beam.

Figure 3.11 The three width measurement locations on the $25\ \mu\text{m} \times 250\ \mu\text{m}$ silicon nitride bi-layered beam.

Before modeling the relation of the residual stress difference of the two silicon nitride films to the deformation along the beam width of bi-layered cantilever beams, the residual stress gradient in the silicon nitride films was analyzed to verify that the deformation (or the radius of curvature) along the bi-layer silicon nitride beam width is caused by the residual stress difference in the two silicon nitride films, i.e., the residual stress gradient across the film thickness does not significantly affect the deformation of the beam. Scanned surface profiles single layer silicon nitride cantilever beams are shown in Figure 3.12 as a 3D model, which shows no significant deformation caused by a residual stress gradient across the thickness of the beam.

Figure 3.12 3D model of the scanned surface profiles of the $15\ \mu\text{m}$ wide single layer silicon nitride cantilever beams.

The surface deflection profile of a $15\ \mu\text{m} \times 250\ \mu\text{m}$ single layer silicon nitride cantilever beam along its length and width are shown in Figure 3.13 and Figure 3.14, respectively (the three width measurement locations are shown in Figure 3.15). Figure 3.13 and Figure 3.14 show no significant deformation caused by the residual stress gradient across the thickness of the beam.

Therefore, the deformation of the bi-layer silicon nitride beam along its width is only caused by the residual mean stress difference in the two films.

Figure 3.13 Profile plot of the 15 μm x 250 μm single layer silicon nitride beam along its length.

Figure 3.14 Profile plot of the 3 locations measured along the width of the 15 μm x 250 μm single layer silicon nitride beam.

Figure 3.15 The three width measurement locations on the $15\text{ }\mu\text{m} \times 250\text{ }\mu\text{m}$ single layer silicon nitride beam.

The relation between the radius of curvature along the width of a silicon nitride bi-layered cantilever beam and the residual stress difference in the two silicon nitride films is derived based on the analysis in [88]. The cross-section (slice A-A) along the width in the central region of a bi-layered cantilever beam is illustrated in Figure 3.16. After the bi-layered cantilever beam is released, the slice A-A in Figure 3.16 is deformed as shown in the inset of Figure 3.16. Making a cut at line B-B of the deformed slice A-A as shown in the inset of Figure 3.16, internal resultant normal forces, F_i , and moments, M_i , act over each thin film (i is the index for the different films) as shown in Figure 3.17 [88][89].

Figure 3.16 Taking a slice (A-A) along the bi-layered beam width.

Figure 3.17 Resulting internal loadings at the cross-section (line B-B) of the width of the bi-layered cantilever beam.

There are no external forces and moments applied to the thin films and the equations of equilibrium are:

$$\sum F = -F_2 - F_1 = 0 \quad (3.1)$$

Taking clockwise as positive, the moments about point P (see Figure 3.17) gives:

$$\sum M_P = -M_2 - M_1 + \frac{F_2 h_1}{2} + F_1 \left(h_1 + \frac{h_2}{2} \right) = 0 \quad (3.2)$$

where \$h_i\$ is the thickness. Therefore, from equations (3.1) and (3.2) gives:

$$F_1 = -F_2 \quad (3.3)$$

$$M_2 + M_1 = F_2 \left(\frac{h_1 + h_2}{2} \right) \quad (3.4)$$

The equation of compatibility for the bi-layered beam is that the difference of the total residual strains between the second film (Nitride 2) and the first film (Nitride 1) must equal to zero at their interface [88][89][95]:

$$\sum \varepsilon_2 - \sum \varepsilon_1 = 0 \quad (3.5)$$

where \$\varepsilon_i\$ is the residual strain. The residual strains for both films due to the residual mean stresses are related by Hooke's Law [95], since \$\sigma = E\varepsilon\$:

$$\varepsilon_{\sigma_1} = \frac{\sigma_1}{\tilde{E}_1} \text{ and } \varepsilon_{\sigma_2} = \frac{\sigma_2}{\tilde{E}_2} \quad (3.6)$$

where $\tilde{E}_i$ and σ_i are the equivalent Young's modulus and the residual mean stresses of the films. Assuming that the bi-layered cantilever beam undergoes a biaxial in-plane residual stress state [96], i.e., the two in-plane stress components (along the X and Y directions of Figure 3.16) are equal to each other and the two in-plane strain components are also equal to each other, the equivalent Young's modulus is determined by [80][82][88][96][97]:

$$\tilde{E}_i = \frac{E_i}{(1-\nu_i)} \quad (3.7)$$

where E_i is the Young's modulus and ν_i is Poisson's ratio of the material. The residual strains due to the resultant internal forces are [95]:

$$\varepsilon_{F_1} = -\frac{F_1}{\tilde{E}_1 b h_1} \text{ and } \varepsilon_{F_2} = -\frac{F_2}{\tilde{E}_2 b h_2} \quad (3.8)$$

where b is the cross-sectional beam width. The residual strains due to the resultant internal moments are determined as follows. The moment-curvature relation due to the bending moment in a beam is [95]:

$$\frac{1}{R_w} = \frac{M}{\tilde{E}I} \quad (3.9)$$

where I is the second moment of inertia and R_w is the radius of curvature along the beam width (see inset of Figure 3.16). The maximum stress in a beam is expressed by the flexure formula [95]:

$$\sigma = \frac{Mz}{I} \quad (3.10)$$

where $z_1 = \frac{h_1}{2}$ for film 1 and $z_2 = -\frac{h_2}{2}$ for film 2. Since $\sigma = E\varepsilon$ and combining equations (3.9) and (3.10) for each film gives:

$$\varepsilon_{M_1} = \frac{h_1}{2R_w} \text{ and } \varepsilon_{M_2} = -\frac{h_2}{2R_w} \quad (3.11)$$

Therefore, combining the equations of (3.6), (3.8), and (3.11) into (3.5) gives:

$$\varepsilon_1 = \frac{\sigma_1}{\tilde{E}_1} - \frac{F_1}{\tilde{E}_1 b h_1} + \frac{h_1}{2R_w} \text{ and } \varepsilon_2 = \frac{\sigma_2}{\tilde{E}_2} - \frac{F_2}{\tilde{E}_2 b h_2} - \frac{h_2}{2R_w} \quad (3.12)$$

and yields the equation of compatibility [88]:

$$\frac{\sigma_2}{\tilde{E}_2} - \frac{F_2}{\tilde{E}_2 b h_2} - \frac{h_2}{2R_w} = \frac{\sigma_1}{\tilde{E}_1} - \frac{F_1}{\tilde{E}_1 b h_1} + \frac{h_1}{2R_w} \quad (3.13)$$

The width of the bi-layered cantilever beam is subjected to a total bending moment caused by the residual stress difference of the two films and the individual moments are related to the radius of curvature in each layer by [74][89][95]:

$$M_1 = \frac{\tilde{E}_1 I_1}{R_w} \text{ and } M_2 = \frac{\tilde{E}_2 I_2}{R_w} \quad (3.14)$$

Substituting the second moment of inertia for a rectangular cross-section into equation (3.14) gives:

$$M_1 = \frac{\tilde{E}_1 h_1^3 b}{12 R_w} \text{ and } M_2 = \frac{\tilde{E}_2 h_2^3 b}{12 R_w} \quad (3.15)$$

Substituting equation (3.15) into equation (3.4) gives:

$$F_2 = \frac{b(\tilde{E}_1 h_1^3 + \tilde{E}_2 h_2^3)}{6R_w(h_1 + h_2)} \quad (3.16)$$

and substituting equation (3.16) into equation (3.13) gives:

$$R_w \left[\frac{\sigma_2 \tilde{E}_1}{\tilde{E}_2} - \sigma_1 \right] - \tilde{E}_1 \left[\frac{h_2}{2} + \frac{h_1}{2} \right] = \frac{(\tilde{E}_1 h_1^3 + \tilde{E}_2 h_2^3)}{6(h_1 + h_2)} \left(\frac{1}{h_1} + \frac{\tilde{E}_1}{\tilde{E}_2 h_2} \right) \quad (3.17)$$

Assuming the two silicon nitride films have the same Young's Modulus, i.e., $\tilde{E}_1 = \tilde{E}_2 = \tilde{E}$, equation (3.17) becomes:

$$[\sigma_2 - \sigma_1] = \left[\frac{(h_1^3 + h_2^3)}{6(h_1 + h_2)} \left(\frac{1}{h_1} + \frac{1}{h_2} \right) + \left(\frac{h_2}{2} + \frac{h_1}{2} \right) \right] \frac{\tilde{E}}{R_w} \quad (3.18)$$

Substituting equation (3.7) in equation (3.18), the residual stress difference is related to the radius of curvature of the bi-layered cantilever beam along the beam width by:

$$\Delta\sigma = \left[\frac{(h_1^3 + h_2^3)}{6h_1 h_2} + \left(\frac{h_1 + h_2}{2} \right) \right] \frac{E}{R_w(1-\nu)} \quad (3.19)$$

where $\Delta\sigma$ is the residual stress difference between film 2 and film 1. Therefore, the residual stress difference for a bi-layer cantilever beam can be obtained via equation (3.19) by measuring the thickness of the two thin films, the Young's modulus of the material and the radius of curvature along the width of the bi-layered beam.

3.5 Measurement of the radius of curvature along the width of bi-layered beams

MetalMUMPs[®] prototypes of 25 μm wide bi-layered cantilever beams (lengths of 400 μm , 450 μm , 500 μm and 550 μm) and 50 μm wide bi-layered cantilever beams (lengths of 500

μm , $550\ \mu\text{m}$, $600\ \mu\text{m}$, $650\ \mu\text{m}$ and $700\ \mu\text{m}$) on loose die 1 were used to determine the residual stress difference of the two silicon nitride films. The $25\ \mu\text{m}$ wide bi-layered cantilever beams were fixed to the edge of the substrate trench as shown in Figure 3.18. The $50\ \mu\text{m}$ wide bi-layered cantilever beams were attached to the free cantilever of a micro bridge mechanism (see Chapter 5) to lift the beams over the substrate trench as shown in Figure 3.19.

Figure 3.18 a) Optical microscope image and b) scanned 3D profile of the $25\ \mu\text{m}$ wide silicon nitride beams fixed to the edge of the substrate trench.

Figure 3.19 a) Optical microscope image and b) scanned 3D profile of the $50\ \mu\text{m}$ wide silicon nitride bi-layered cantilever beams suspended by the micro bridge mechanism.

All the 50 μm wide bi-layered cantilever beams attached to the micro bridge mechanism used to determine the residual stress difference of the two silicon nitride films were all successfully suspended above the substrate as shown in Figure 3.19. The beams in Figure 3.19 were then sent for a SEM image after their surface profiles were measured by the Zygo[®] optical interferometer. Unfortunately, the beams were deformed by the SEM and the beams resulted in sticking to the surface of the substrate trench as shown in Figure 3.20 and Figure 3.21.

Figure 3.20 SEM image of the 50 μm wide bi-layered cantilever beams sticking to the surface of the substrate trench.

Figure 3.21 Optical microscope image of the 50 μm wide bi-layered cantilever beams sticking to the surface of the substrate trench.

All the bi-layered cantilever beam prototypes were measured for their surface profiles using the MetroPro Films Application of the Zygo[®] optical interferometer. A scan length of 10 μm was used in measuring the 25 μm wide beams and a scan length of 40 μm was used in the measuring the 50 μm wide beams. The above scan lengths were the typical ones used for the surface profile measurements. The 20X objective lens was used with the 0.5X or the 1X magnification of the scope. Within the surface profile of each beam, “Poly” slice lines were drawn across the width of the beam as illustrated in Figure 3.22 (116 slice lines are shown in Figure 3.22) and the data points of the profile plot (see Figure 3.22, white circle) of all the slice lines were saved in an “.xls” file. The slice lines were equally spaced apart along the beam length depending on the lens and magnification used to scan the surface profile of the beam. For example, the slice lines in Figure 3.22 were spaced 4 pixels apart along the length of the beam using the 20X objective lens with the 1X internal magnification of the optical interferometer.

Using the built in “RadCrv” function in the MetroPro Films Application, the radius of curvature of each slice line was automatically determined by the application and was listed in a process table (see Figure 3.22, white rectangle) [60][61]. The process table was then saved as an “.xls” file and was used in the residual stress difference calculations.

Using the saved data points of the profile plot of all the slice lines, the radius of curvature of each slice line was calculated using a Maple code for circle fitting developed in [100] to check the accuracy of the radius of curvature measurements calculated by the MetroPro Films Application. A modified version of the Maple code developed in [100] is listed in Appendix D. All the values determined by the MetroPro Films Application were within 0.3% of the Maple calculated values. Hence, the radii of curvature acquired by the Zygo[®] optical interferometer were used in the subsequent residual stress difference calculations.

Figure 3.22 Measuring the radius of curvature along the beam width of the bi-layered cantilever beam using “Poly” slice lines in the MetroPro Films Application.

Figure 3.23 illustrates a 3D model of the scanned surface profile of the 50 μm wide and 500 μm long silicon nitride bi-layered cantilever beam and a curvature deformation along the beam width is clearly seen. Figure 3.24 shows the measurement results of the radii of curvature along the beam width of the silicon nitride bi-layered cantilever beam that is 50 μm wide and 500 μm long. About 56% of the beam length has a consistent radius of curvature along the beam width in the central region of the beam, which has an average and standard deviation (σ_p via equation (2.1)) of $662.7 \pm 3.76 \mu\text{m}$, as shown in Figure 3.24. All the radius of curvature along the beam width measurements determined by the Zygo[®] optical interferometer in the central region of each beam are listed in Appendix C.

Figure 3.23 3D model of a scanned surfaced profile of the 50 μm x 500 μm silicon nitride bi-layer cantilever beam.

Figure 3.24 Radius of curvature along the width measurements of the 50 μm x 500 μm silicon nitride bi-layered cantilever beam.

The average and standard deviation (σ_p via equation (2.1)) of the radius of curvature along the beam width measurements of each 50 μm and 25 μm wide silicon nitride bi-layered cantilever beam are listed in Table 3.1 and are shown in Figure 3.25. Since the radii of curvature along the beam width are all positive and the residual stresses in both films are tensile [74], a positive residual stress difference is expected, i.e., the residual stress in the Nitride 2 layer is greater than the residual stress in the Nitride 1 layer. The measured results of the radius of

curvature along the beam width in Table 3.1 are different between the 50 μm wide and 25 μm wide beams because the residual stress difference is different between the two silicon nitride layers for each beam width.

Table 3.1 Measured average and standard deviation results of the radius of curvature along the beam width of each 50 μm and 25 μm wide silicon nitride bi-layered beam.

Beam Length (μm)	Measured R_w (μm)	
	50 μm wide	25 μm wide
400	n/a	567.6 ± 4.89
450	n/a	572.8 ± 3.26
500	662.7 ± 3.73	583.8 ± 6.38
550	665.4 ± 5.15	577.7 ± 6.07
600	662.6 ± 4.22	n/a
650	662.1 ± 4.03	n/a
700	662.1 ± 3.45	n/a

Figure 3.25 Radius of curvature measurements of all the 50 μm and 25 μm wide silicon nitride bi-layered beams.

3.6 Residual stress difference determination for the two silicon nitride films

From each measured radius of curvature along the beam width in Table 3.1, the residual stress difference of the two silicon nitride films was calculated via equation (3.19) for each beam. The properties obtained earlier, i.e., measured thicknesses for loose die 1, extracted Young's Modulus and assumed Poisson's ratio (from Chapter 2), were used in the calculation of the residual stress difference of the two silicon nitride films for each beam. For example, taking $E = 209 \text{ GPa}$, $\nu = 0.23$, $h_1 = 0.321 \text{ }\mu\text{m}$, $h_2 = 0.25 \text{ }\mu\text{m}$ and $R_w = 662.7 \text{ }\mu\text{m}$ for the $50 \text{ }\mu\text{m}$ wide and $500 \text{ }\mu\text{m}$ long silicon nitride bi-layer cantilever beam, the residual stress difference computes to $\Delta\sigma = 158.4 \text{ MPa}$. Thus, the results of the residual stress difference are listed in Table 3.2 and are shown in Figure 3.26 for each $50 \text{ }\mu\text{m}$ and $25 \text{ }\mu\text{m}$ wide silicon nitride bi-layered cantilever beam. From all the values given in Table 3.2, an overall average and standard deviation (σ_p via equation (2.1)) of $169.0 \text{ MPa} \pm 12.04 \text{ MPa}$ was determined for the residual stress difference of the two MetalMUMPs[®] silicon nitride films.

Table 3.2 Calculated values of the residual stress difference for each $50 \text{ }\mu\text{m}$ and $25 \text{ }\mu\text{m}$ wide silicon nitride bi-layered beam.

Beam Length (μm)	$\Delta\sigma \text{ (MPa)}$	
	50 μm wide	25 μm wide
400	n/a	184.9
450	n/a	183.2
500	158.4	179.8
550	157.7	181.7
600	158.4	n/a
650	158.5	n/a
700	158.5	n/a

Figure 3.26 Calculated values of the residual stress difference for each 50 μm and 25 μm wide silicon nitride bi-layered beam.

3.7 Numerical bi-layered beam simulations

Numerical simulations were conducted in ANSYS® 11.0 to verify the extracted residual stress difference of the two MetalMUMPs® silicon nitride films. This was accomplished by comparing the average radius of curvature along the width located far from the beam boundaries of each simulated beam model to the measured radius of curvature along the width of each silicon nitride bi-layered cantilever beam in Table 3.1.

Each 50 μm wide and 25 μm wide silicon nitride bi-layered beam from Table 3.2 was modeled in ANSYS® using the measured Nitride 1 and Nitride 2 thicknesses from Table 2.2 and the dimensions given in Table 3.3. The lengths given in Table 3.3 for the simulations were longer because the extra length was used to simulate the fixed boundary condition of the fabricated 50 μm wide and 25 μm silicon nitride bi-layered beams. The two Nitride layers were modeled as separate volumes and were glued together to complete the bi-layered beam model.

The element type used for the two Nitride volumes was the Brick 20 node 186 element (SOLID186) [101]. The SOLID186 element type was chosen because the bi-layered beam models have an orthogonal geometry.

Table 3.3 Lengths used in the bi-layered beam models.

	50 μm wide	25 μm wide
Prototype beam length (μm)	Beam length used for ANSYS simulations (μm)	
400	n/a	410
450	n/a	460
500	540	510
550	590	560
600	640	n/a
650	690	n/a
700	740	n/a

The 50 μm wide bi-layered beam models were meshed with an element size of 5 μm and the 25 μm wide bi-layered beam models were meshed with an element size of 2.5 μm . Various element sizes were tested and the above element sizes for the 50 μm wide and the 25 μm wide bi-layered beam models were sufficient to obtain accurate results. The nodes that were within 40 μm from the edge of the model on the top surface of the Nitride 2 volume were fixed in all directions for all the 50 μm wide bi-layered beam models (see Figure 3.27). The nodes of all the 25 μm wide bi-layered beam models were fixed in all directions at the edges within 10 μm from the edge of the model at one end of the bi-layered beam as shown in Figure 3.28.

Figure 3.27 The nodes fixed for the 50 μm wide bi-layered beam models.

Figure 3.28 The nodes fixed for the 25 μm wide bi-layered beam models.

The residual stress difference was applied as the residual mean stress along the X and Y directions to simulate the biaxial residual mean stress in the Nitride 2 volume (top layer) of the bi-layered beam model by using the INISTATE command in ANSYS® [102][103]. The Nitride 1 volume (bottom layer) was assumed to have a zero residual mean stress and thus the difference in residual stress between the two Nitride volumes will simulate a residual stress difference in the bi-layer beam model. The residual stress difference of each beam in Table 3.2 was applied to their respective bi-layered beam models. For example, for the 50 μm wide and 500 μm long silicon nitride bi-layered cantilever beam, the residual stress difference of 158.4 MPa from Table 3.2 was applied to the Nitride 2 volume of the 50 μm wide and 500 μm long bi-layered beam model. Then each bi-layered beam model was simulated for its deformation. A simulated 50 μm x 500 μm silicon nitride bi-layer cantilever beam model is illustrated in Figure 3.29 showing that the beam deforms into a curvature shaped profile along the width and length directions.

Figure 3.29 The simulated 50 μm x 500 μm silicon nitride bi-layered cantilever beam deformed by the residual stress difference.

From each simulated bi-layered beam model, the x, y, and z initial nodal coordinates and the final x, y and z nodal displacements were retrieved. Using the nodal coordinates and nodal displacements, the radius of curvature along the beam width using the Maple code for circle fitting developed in [100] at four locations in the central region of the bi-layered beam model (far from the fixed and free ends of the beam model) was calculated for each simulated bi-layered beam model. The calculated average and standard deviation (σ_p via equation (2.1)) results of the radius of curvature along the beam width for each simulated 50 μm wide and 25 μm wide silicon nitride bi-layer cantilever beam are listed in Table 3.4 and are shown in Figure 3.30 with the results from Figure 3.25 for comparison.

The experimentally measured and the simulated results of the radius of curvature along the beam width differ by less than 0.2% for both the 50 μm wide and the 25 μm wide silicon

nitride bi-layered cantilever beams. From this comparison, it is clear that the experimentally measured and the simulated results of the radius of curvature along the beam width agree very well. Therefore, the extracted residual stress difference is verified by this comparison and demonstrates the effectiveness of equation (3.19) developed by the analytical model in Section 3.4.

Table 3.4 Simulated results of the radius of curvature along the beam width for each silicon nitride bi-layered cantilever beam.

Beam Length (μm)	Simulated R_w (μm)	
	50 μm wide	25 μm wide
400	n/a	567.4 ± 0.68
450	n/a	571.7 ± 0.60
500	662.1 ± 0.34	582.9 ± 1.28
550	664.7 ± 0.12	577.4 ± 0.76
600	662.0 ± 0.17	n/a
650	661.0 ± 0.68	n/a
700	662.3 ± 0.93	n/a

Figure 3.30 Comparison of the simulated results and the measured results of the radius of curvature along the width of each silicon nitride bi-layered beam.

Chapter 4 Extraction of the Young's Modulus and the Residual Stress Gradient of the MetalMUMPs[®] Electroplated Nickel Film

The Young's modulus and the residual stress gradient across the thickness, of the MetalMUMPs[®] nickel film are not currently available [24]. Values of 202 GPa [14] or 180 GPa [25] are assumed for the Young's modulus of the nickel film by MetalMUMPs[®] users. Even with a small magnitude of the residual stress gradient across the thickness of the nickel film causes significant undesired deformations of suspended MetalMUMPs[®] nickel structures [14][18][19]. For example, it has been reported that the residual stress gradient of the nickel film caused undesired deformation of a moving electrode of a MetalMUMPs[®] tuneable capacitor [14]. The undesired deformation and its effects on the performance of the tuneable capacitor cannot be quantified without information about the residual stress gradient of the nickel film. In this chapter, the Young's modulus and the residual stress gradient of the MetalMUMPs[®] nickel film are extracted in Section 4.1 and in Section 4.2, respectively.

4.1 Extraction of the Young's modulus of the MetalMUMPs[®] nickel film

The extraction of the Young's modulus of the nickel film in this section uses the same approach to extract the Young's modulus of the silicon nitride films in Chapter 2. In Section 4.1.1, the fabricated nickel cantilever beam prototypes are described. The Young's modulus of the nickel film is then experimentally measured through the following approach. First, the nickel cantilever beam prototypes are measured for their thicknesses in Section 4.1.2. Second, the first mode resonant frequencies of the nickel cantilever beams are measured in Section 4.1.3. Last, in Section 4.1.4, the Young's modulus of the nickel film is extracted based on the measured resonant frequencies via numerical simulations.

4.1.1 Nickel prototypes

Nickel cantilever beam prototypes as shown in Figure 4.1 were fabricated using the MetalMUMPs® process. Three MetalMUMPs® loose dies with seven cantilever beams on each loose die were measured to extract the Young's modulus of the nickel film. All the beams have the same width of 100 μm . The beam length varies from 1000 μm to 700 μm with a decrement of -50 μm . Each beam is a composite composed of three layers, i.e., a copper plating base (Cu) layer, an electroplated nickel (Ni) layer, and a top gold (Au) layer [13], as shown in Figure 4.2. The nominal thickness of each layer of the composite are listed in Table 4.1.

Figure 4.1 Nickel cantilever beams.

Figure 4.2 Layers of the composite beam.

Table 4.1 The nominal thickness of each layer of the composite [13].

Film	Nominal Thickness (μm)
Copper	0.55
Nickel	20
Gold	0.5

4.1.2 Nickel thickness measurements

The nickel thickness of each nickel cantilever beam was measured using the Zygo[®] optical interferometer and was used for building 3D beam models for numerical simulations. The total thickness of each beam was first obtained by measuring the height difference from the top gold layer of the beam to the top silicon nitride layer on the substrate along the line A-A (see Figure 4.3) and then subtracting the gap of $1.1\ \mu\text{m}$, which is formed by the sacrificial oxide 2 layer. Figure 4.4 shows the measured nickel thicknesses of all the nickel cantilever beams, which was obtained by subtracting the nominal thickness of the copper and the gold layers (from Table 4.1) from the total measured thickness of the beams. Processed thickness measurements the nickel cantilever beams are listed in Appendix C.

Figure 4.3 Measuring the thickness of the nickel cantilever beam.

Figure 4.4 Nickel thickness measurements for each nickel cantilever beam.

4.1.3 Resonant frequency measurements of the nickel cantilever beams

Piezoelectric transducers (Figure 4.5) were also used to excite the nickel cantilever beams to find their first mode resonant frequencies. The setup of the Zygo[®] optical interferometer was conducted using the general procedure in Appendix A. The resonant frequencies of the nickel cantilever beams were measured using the same procedure in Section 2.4.3, but with the following differences: 1) Frequency increments of 500 Hz, 100 Hz, and 10 Hz were used for the manual sweep, coarse sweep and fine sweep, respectively; 2) Voltage amplitudes of 0.01 V up to 1V were used depending on the length of the beam; and 3) Frequency scanning ranges of ± 1000 Hz and ± 100 Hz were used for the coarse sweep and fine sweep, respectively. Figure 4.6 shows the measured frequency response curve of one sample nickel cantilever beam with a length of 800 μm and the first mode resonant frequency of 20350 Hz is determined from the plot. The mode shape of one sample nickel cantilever beam is shown in Figure 4.7 oscillating at its first

mode resonance frequency when the beam is deflected at different phases. The measured resonant frequencies of all the 21 nickel cantilever beams are shown in Figure 4.8 and are listed in Appendix C.

Figure 4.5 The piezoelectric transducer used to excite the nickel cantilever beams.

Figure 4.6 Frequency response curve for an 800 μm long nickel cantilever beam.

a) Phase 0°

b) Phase 240°

Figure 4.7 Deflection profiles of a nickel cantilever beam oscillating at its first mode resonance frequency when the phase is at a) 0° and b) 240° .

Figure 4.8 Measured first mode resonant frequencies of all the nickel cantilever beams.

4.1.4 Young's modulus extraction for the nickel film

Similar to Section 2.5.1, numerical simulations were conducted in CoventorWareTM [69] to extract the Young's modulus of the nickel film because the analytical equations cannot account for the effects of the depression support (Figure 4.9a) of the fabricated nickel cantilever beams. As shown in Figure 4.9a, this type of support is a more flexible boundary condition than the ideal support which is assumed by the analytical equation (Figure 2.41). The depression support is formed due to the fabrication steps used in the MetalMUMPs[®] process [13].

3D composite beam models of each beam length were built using the foundry MetalMUMPs[®] process included in CoventorWareTM [69], the measured nickel thicknesses from Figure 4.4, and the nominal thickness of the gold and copper layers from Table 4.1. The composite beam models could not be meshed using Manhattan Bricks in CoventorWareTM and thus were meshed using 10-node Tetrahedrons since the thickness of the copper and gold layers

were very thin in comparison to the thick nickel layer. Tetrahedrons with various element sizes were tested and it was found that an element size of 15 μm was sufficient to obtain accurate results. A composite beam model is shown in Figure 4.9 with the depression support included. The bottom surface of the depression support of each beam model was anchored (see Figure 4.9b). The material properties of each layer used in the simulations are listed in Table 4.2. All the simulations used the lanczos mode solution method.

Figure 4.9 The 3D nickel cantilever beam model in CoventorWareTM.

Table 4.2 Material properties of the three layers [25].

Layer	Young's Modulus (GPa)	Poisson Ratio
Copper	128	0.36
Nickel	-	0.3
Gold	57	0.35

Each beam was simulated by varying the Young's modulus of the nickel film until the simulation result of the first mode resonant frequency matches the measured result (Figure 4.8) with an accuracy of ± 10 Hz. Thus, the extracted Young's modulus of each beam is listed in Appendix C and is shown in Figure 4.10, which shows that the Young's modulus of the

MetalMUMPs[®] nickel film is from 155 GPa to 164 GPa with an average and standard deviation (σ_p via equation (2.1)) of $159 \text{ GPa} \pm 2.6 \text{ GPa}$.

Figure 4.10 The extracted Young's modulus of the MetalMUMPs[®] nickel film.

4.2 Extraction of the residual stress gradient of the MetalMUMPs[®] nickel film

The residual mean stress in the MetalMUMPs[®] nickel film has been provided [13]. However, the residual stress gradient of the MetalMUMPs[®] nickel film is currently not available. Consequently, it is difficult to predict the performance and then optimize MetalMUMPs[®] devices such as RF tuneable capacitors and switches, which require flat moving electrode plates. The most common technique of characterizing the residual stress gradient in thin films is to measure the deformation of a cantilever beam made of the thin film material [75][77][81][82]. It is convenient to use cantilever beams to extract the residual stress gradient if the residual stress gradient is positive [37][47][75][80]. However, if the residual stress gradient is negative,

trenches or through-wafer holes underneath the beams are required to accommodate the downward deflection of the beams [106][107]. Opening trenches or through-wafer holes is either impossible for some micro fabrication processes or would significantly increase the process complexity.

In this section, the residual stress gradient of the MetalMUMPs[®] nickel film is determined as follows. The prototypes used to extract the residual stress gradient of the nickel film are introduced in Section 4.2.1. Next, experimental curvature measurements are in Section 4.2.2. Finally, in Section 4.2.3, the residual stress gradient of the MetalMUMPs[®] nickel film is extracted.

4.2.1 Free beam prototypes

In this section, the prototypes of a stress gradient induced free beam mechanism are introduced for extracting the residual stress gradient of the MetalMUMPs[®] nickel film. The free beam mechanism consists of a bridge beam, a connecting beam and a free beam as shown in Figure 4.11a. The bridge beam is connected to two anchor pads through two narrow support beams. The free beam is connected to the middle of the bridge beam through the connecting beam. Due to a negative residual stress gradient in the thin film, bending moments are induced in both the bridge beam and the free beam, which bends the bridge beam and the free beam into a convex shape after being released Figure 4.11b. The two ends of the free beam bend downwards relative to the middle of the free beam. Since the free beam is connected to the middle of the convexed bridge beam, it is raised by the bridge beam. Thus, the two ends of the free beam can be lifted high above the substrate if the bridge beam is long enough.

Figure 4.11 The residual stress induced free beam mechanism.

Figure 4.12 shows one prototype of the free beam mechanism with the free beam fabricated by the MetalMUMPs[®] process. Compared to the design in Figure 4.11, finger structures were added to the bridge beam for observing the deflection of the bridge beam without significantly affecting the bending stiffness of the bridge beam. A wide bridge beam (200 μm) and a wide free beam (100 μm) were used for the convenience of measuring their surface profiles using the Zygo[®] optical interferometer. In addition, a wide bridge beam was needed to obtain a large residual stress gradient to induce a large bending moment to pull the two ends of the bridge beam against the support beams to form a large convex shape, such that the free beam can be lifted as high as possible. The trenches underneath the bridge beam and the connecting beam were for facilitating the release of the beams. The trench underneath the free beam was for accommodating the downward deflection of the two ends of the free beam. The dimensions of the free beam mechanism are listed in Table 4.3. Figure 4.12a shows the convexed bridge beam and the convexed free beam. Figure 4.12b and Figure 4.12c show that the two ends of the free beam are free (not touching the surface of trench) because the free beam was lifted sufficiently high by the bridge beam through the connecting beam.

a) Side view of the convex bridge and free beams

b) Left end of the free beam

c) Right end of the free beam

Figure 4.12 SEM images of the MetalMUMPs® free beam mechanism.

Table 4.3 Dimensions of the free beam mechanism.

	Bridge beam	Connecting beam	Free beam	Support beam	Finger Structure
Length (μm)	5240	1000	3970	600	550
Width (μm)	200	200	100	8	30

4.2.2 Curvature measurements

Six prototypes (Prototype 1 to Prototype 6) of the free beam mechanism were measured using the Zygo® optical interferometer. Figure 4.13 and Figure 4.14 show the surface profile of the Prototype 1 free beam mechanism measured. A slice line A-A was drawn along the bridge beam and another slice line B-B was drawn along the free beam within the surface profile of the free beam mechanism as shown in Figure 4.13a.

The measured results in Figure 4.13 and Figure 4.14 show that the bridge beam and the free beam are both in a convex shape with convex heights of $21\text{ }\mu\text{m}$ (Figure 4.14a) (excluding the contribution of the two support beams) and $40\text{ }\mu\text{m}$ (Figure 4.14b), respectively, which confirms there is a negative residual stress gradient in the nickel film. Using the free beam mechanism, the long (unreleased length of $3970\text{ }\mu\text{m}$) free beam (its two ends are released and free of residual stress after being released) was used for extracting the residual stress gradient in

the MetalMUMPs® nickel film. Due to long length of the free beam, the curvature of the free beam can be accurately calculated based on the measured surface profile of the beam, which leads to an accurate extraction of the residual stress gradient of the nickel film. Lateral dimensions of the free beam are listed in Table 4.3.

Figure 4.13 Surface profile of the Prototype 1 free beam mechanism.

Figure 4.14 Surface profiles of the bridge beam and the free beam.

The curvatures of the convexed free beams can be calculated from their measured surface profiles. Before calculating the curvature, the noise in the measured surface profile data was filtered out. This was accomplished by setting a filtering curve, $f(x_i)$, and comparing the measured surface profile data, $v(x_i)$, with the data on the filtering curve at each location, x_i , using the following formula:

$$v(x_i) = \begin{cases} v(x_i) & v(x_i) > f(x_i) \\ v(x_{i-1}) & v(x_i) \leq f(x_i) \end{cases} \quad (4.1)$$

The filtering curve was a polynomial function obtained by approximating the original data of the surface profile using the least-squares method and then shifted down by 1.5 μm , as shown in Figure 4.15. Figure 4.16 shows the fitted arc of the free beam surface profile of Prototype 1.

Figure 4.15 Surface profile of the Prototype 1 free beam.

Figure 4.16 Circle fitting of the surface profile of the Prototype 1 free beam.

Various algorithms are available for fitting circles to discrete points [98][99]. In this section, the curvatures of the free beams were calculated using the Maple code for circle fitting developed in [100]. The calculated curvature of the free beam of each prototype is listed in Table 4.4.

Table 4.4 Measured results of the free beam mechanism prototypes.

Prototype	Thickness of the nickel film (μm)	Curvature of free beam(μm^{-1})	Residual stress gradient ($\text{MPa}/\mu\text{m}$)	Residual stress change across the thickness (MPa)
1	17.94	1/46316	-5.49	-98.53
2	21.62	1/55365	-4.51	-97.44
3	22.75	1/57321	-4.33	-98.57
4	22.30	1/57828	-4.30	-95.95
5	19.00	1/50292	-5.03	-95.50
6	21.70	1/53867	-4.63	-100.48

4.2.3 Residual stress gradient extraction for the nickel film

The free beam of the free beam mechanism is a three layered composite beam as shown in Figure 4.17 [13]. The bending moment in the free beam is expressed as [23]:

$$M = \frac{\tilde{E}_{Ni}I_{Ni} + \tilde{E}_{Cu}I_{Cu} + \tilde{E}_{Au}I_{Au}}{R_{FB}} \quad (4.2)$$

where I_{Ni}, I_{Cu}, I_{Au} are the moments of inertia (for a rectangular cross-section) of the nickel, copper, and gold layers, respectively, about the neutral axis, which is assumed to be located at the centroid of the nickel layer (see Figure 4.17), $1/R_{FB}$ is the curvature, and $\tilde{E}_{Ni}, \tilde{E}_{Cu}, \tilde{E}_{Au}$ are the equivalent effective Young's modulus of the nickel, copper, and gold respectively, and are calculated by equation (3.7).

Figure 4.17 The three layered composite.

The free beam is an asymmetrical three layered composite beam since the copper layer and the gold layer have different Young's moduli and thicknesses. The bending moment caused by the mean residual stress (100 MPa tensile [13]) in the nickel layer due to the asymmetrical structure of the composite beam is neglected. The residual stresses in both the gold and the copper layers are also neglected due to their small thickness in comparison to the nickel layer [108]. Thus, the bending moment is only induced by the residual stress gradient in the nickel layer and is expressed as:

$$M = \Gamma \cdot I_{Ni} \quad (4.3)$$

where Γ is the residual stress gradient. Substituting equation (4.3) into equation (4.2) gives:

$$\Gamma = \frac{\tilde{E}_{Ni} I_{Ni} + \tilde{E}_{Cu} I_{Cu} + \tilde{E}_{Au} I_{Au}}{R_{FB} I_{Ni}} \quad (4.4)$$

Therefore, the residual stress gradient in the MetalMUMPs[®] nickel film is related to the curvature of the free beam by equation (4.4).

The nickel film thickness of the free beam mechanism was obtained by measuring the height from the top surface of the anchor pad (see Figure 4.12a) to the top surface of the silicon nitride layer (similar to measuring the thickness of the nickel cantilever beams in Section 4.1.2)

and then subtracting the nominal thickness of the copper, gold, chromium (10 nm) and platinum (25 nm) layers. The measured nickel thickness of each free beam mechanism is listed in Table 4.4. Using the curvatures from Table 4.4, the Young's modulus of 159 GPa for the nickel film (from Section 4.1.4), the material properties from Table 4.2, the nickel thicknesses from Table 4.4, and the nominal thickness of the copper and gold layers from Table 4.1, the residual stress gradient of the MetalMUMPs® nickel film was determined via equation (4.4) for the six prototypes. Thus, the results of the residual stress gradient of the MetalMUMPs® nickel film are listed in Table 4.4 and ranges from -5.49 MPa/μm to -4.30 MPa/μm as shown in Figure 4.18 with an average and standard deviation (σ_p via equation (2.1)) of -4.72 MPa/μm $\pm$ 0.42 MPa/μm. Also, the results of the total residual stress change across the nickel film thickness are listed in Table 4.4 and are shown in Figure 4.19 with an average and standard deviation (σ_p via equation (2.1)) of -97.74 MPa $\pm$ 1.69 MPa.

Figure 4.18 Calculated results of the residual stress gradient of the MetalMUMPs® nickel film.

Figure 4.19 Calculated results of the residual stress change across the thickness of the MetalMUMPs[®] nickel film.

Figure 4.18 shows that the magnitude of the residual stress gradient is inversely proportional to the nickel film thickness (note the negative sign for the residual stress gradient). This linear trend might be caused by some factors, which contribute to the bending moment in the free beam but were not considered when extracting the residual stress gradient in the nickel film. Those factors include the mean residual stress in the nickel layer, which generates a bending moment due to the asymmetric structure of the beam, and the residual stresses in the gold and the copper layers, which also could generate bending moments in the beam. The obtained residual stress gradient of the nickel film would have significant error if the residual stresses in the copper and gold layers cause a significant bending moment because the above calculations assume they do not cause a significant bending moment.

Chapter 5 The Micro Bridge Mechanism

The purpose of the micro bridge mechanism is for lifting long silicon nitride bi-layer cantilever beams over the substrate and suspending the beams for the determination of the residual stress difference of the two silicon nitride films. Without the micro bridge mechanism, long silicon nitride cantilever beams result in sticking to the surface of the substrate trench as shown in Figure 2.19 due to external forces such as the centripetal forces generated during the rinsing and drying stages in the micro fabrication process.

In this chapter, the micro bridge mechanism is introduced. First, the design of the micro bridge mechanism is described in Section 5.1. Second, the typical deflections of the micro bridge mechanisms are determined in Section 5.2 by numerical simulations. Third, an analytical model to determine the deflection of the micro bridge mechanism is developed in Section 5.3. Fourth, in Section 5.4, the measured deflections of each fabricated micro bridge mechanism are conducted with the Zygo[®] optical interferometer. Fifth, the calculated deflections of each fabricated micro bridge mechanism using the analytical model and conducting numerical simulations are described in Section 5.5. Finally, the findings in developing and analyzing the micro bridge mechanism are summarized in Section 5.6.

5.1 Design

The micro bridge mechanism uses the MetalMUMPs[®] nickel, copper and gold layers as its primary structural material [13] and is an optimized extension of the free beam mechanism that was introduced in Section 4.2. The micro bridge mechanism applies the concept of the negative residual stress gradient across the thickness in the nickel layer to displace out-of-plane the tip of the free cantilever of the micro bridge mechanism through the double cantilever beams

deflecting downward (also induced by the residual stress gradient in the nickel layer) with the double bridge beam and support beams acting as a pivoting structure (like a see-saw) as shown in Figure 5.1. In addition, the double bridge beam of the micro bridge mechanism is induced by the residual stress gradient in the nickel layer, which generates a bending moment to pull its two ends against the support beams to form a convex shape, such that the free cantilever is lifted higher. The extra height gained from the displacement allows for long silicon nitride cantilever beams attached to the free cantilever to be suspended freely above the substrate. The optimized part of the micro bridge mechanism is that it takes 30% less space on the loose die than the free beam mechanism.

Figure 5.1 SEM photo of the micro bridge mechanism (side view).

Eleven micro bridge mechanisms were fabricated by MetalMUMPs[®] process. Six micro bridge mechanisms use a squared serpentine spring design (see Figure 5.2) and the other five use a curved serpentine spring design (see Figure 5.3). A SEM photo of the curved serpentine spring micro bridge mechanism is shown in Figure 5.4 with its individual parts labelled. The squared

serpentine spring micro bridge mechanism is shown in Figure 5.5. One of the six squared serpentine spring micro bridge mechanisms (Prototype C1) includes a free beam at the end of its free cantilever for the purpose of obtaining the residual stress gradient of the nickel layer and using the extracted residual stress gradient for conducting deflection calculations for each fabricated micro bridge mechanism. A SEM image of the Prototype C1 micro bridge mechanism is illustrated in Figure 5.6 with the free beam attached to the end of the free cantilever.

Several of the silicon nitride beams that were attached to the free cantilever of the micro bridge mechanism were sticking to the surface of the substrate trench and several were successfully suspended as shown in Figure 5.1, Figure 5.4, and Figure 5.5. Another case is shown in Figure 5.6, where the silicon nitride beams with metal masses attached to the one end of the beam and the other end attached the micro bridge mechanism were sticking to the surface of the substrate trench. Since the photos of micro bridge mechanism were taken in the SEM, part of the cause of the silicon nitride beams to stick to the surface of the substrate trench is due to the SEM and external forces such as the centripetal forces generate during the rinsing and drying stages of the micro fabrication process.

The design of the micro bridge mechanism is described as follows. There are two types of serpentine springs: the squared type (Figure 5.2) and the curved type (Figure 5.3). The entire micro bridge mechanism is anchored to the substrate with four anchor pads. Two double cantilever beams are connected to each other by two serpentine springs and a spring connector (see Figure 5.2 or Figure 5.3). The fixed ends of the double cantilever beam are anchored to the substrate via the anchor pads. The double bridge beam is connected to two support beams that are anchored to the substrate via the anchor pads. The connecting beam and a serpentine spring connect the double bridge beam to the spring connector (see Figure 5.2 or Figure 5.3). The fixed

end of the free cantilever is attached to the double bridge beam. The free beam is attached to the end of the free cantilever only in the Prototype C1 micro bridge mechanism (see Figure 5.6).

Table 5.1 lists all the dimensions of each part of the squared serpentine spring micro bridge mechanisms and Table 5.2 lists all the dimensions of each part of the curved serpentine spring micro bridge mechanisms. Technical drawings of the individual parts of the micro bridge mechanism are listed in Appendix B.

Figure 5.2 The squared serpentine spring.

Figure 5.3 The curved serpentine spring.

Figure 5.4 The curved serpentine spring micro bridge mechanism (Prototype A2).

Figure 5.5 The squared serpentine spring micro bridge mechanism (Prototype A4).

Figure 5.6 The Prototype C1 micro bridge mechanism with the free beam attached to the free cantilever.

Table 5.1 Dimensions for the squared serpentine spring micro bridge mechanism designs.

Part/Prototype	Length (μm) x Width (μm)			
	A1	A4	B1, B3, B4	C1
Free Cantilever	860 x 100	864 x 100	860 x 100	*905 x 100
Connecting Beam	140 x 100	150 x 100	140 x 100	140 x 100
Double Bridge Beam	2220 x 280	2220 x 280	2120 x 280	2120 x 280
Double Bridge Beam - long hole	880 x 100	880 x 100	830 x 100	830 x 100
Double Bridge Beam - center hole	100 x 100	100 x 100	100 x 100	100 x 100
Support Beam	500 x 8	500 x 8	550 x 10	550 x 10
Double Cantilever Beam	1500 x 280	1500 x 280	1500 x 280	1500 x 280
Double Cantilever Beam - long hole	1320 x 100	1320 x 100	1320 x 100	1320 x 100
Spring Connector	200 x 80	200 x 108	200 x 80	200 x 80
Spring Connector - hole	150 x 30	140 x 40	150 x 30	150 x 30
Squared Serpentine Spring				
– side length	200	200	200	200
– width	10	8	10	10
– end to end distance	70	56	70	70
– gap	10	8	10	10
Free Beam	n/a	n/a	n/a	3050 x 90

*The width of the free beam of Prototype C1 adds 90 μm more to the length of the free cantilever.

Table 5.2 Dimensions for the curved serpentine spring micro bridge mechanism designs.

Part/Prototype	Length (μm) x Width (μm)			
	A2	A3	A5	B2, B5
Free Cantilever	860 x 100	860 x 100	874 x 100	860 x 100
Connecting Beam	140 x 100	140 x 100	140 x 100	140 x 100
Double Bridge Beam	2120 x 280	2220 x 280	2220 x 280	2120 x 280
Double Bridge Beam - long hole	830 x 100	880 x 100	880 x 100	830 x 100
Double Bridge Beam - center hole	100 x 100	100 x 100	100 x 100	100 x 100
Support Beam	550 x 10	500 x 8	500 x 8	550 x 10
Double Cantilever Beam	1430 x 280	1430 x 280	1438 x 280	1430 x 280
Double Cantilever Beam - long hole	1250 x 100	1250 x 100	1258 x 100	1250 x 100
Spring Connector	136 x 116	136 x 116	136 x 104	136 x 116
Spring Connector - hole	76 x 56	76 x 56	76 x 44	76 x 56
Curved Serpentine Spring				
– side length	200	200	200	200
– width	10	10	8	10
– end to end distance	112	112	104	112
– gap	25	25	24	25

5.2 Typical deflections of the micro bridge mechanisms

Numerical simulations of obtaining the typical deflection of the free cantilever of each of the eleven micro bridge mechanisms were conducted in CoventorWare™ [69]. The micro bridge mechanism models were built using the foundry MetalMUMPs® process included in CoventorWare™ using the dimensions given in Table 5.1 and Table 5.2, and the nominal thickness of the three layers from Table 4.1. The material properties from Table 4.2 with the Young's modulus of 159 GPa for the nickel layer and the residual stress gradient of -4.72 MPa/μm from Section 4.2.3 were applied to each model. The models could not be meshed using Manhattan Bricks and thus were meshed using 10-node Tetrahedrons since the thickness of the copper and gold layers were very thin in comparison to the thick nickel layer. Tetrahedrons with various element sizes were tested and it was found that an element size of 19 μm was sufficient to obtain accurate results. Each micro bridge mechanism model was fixed at their four anchor pads and the residual stress gradient was applied in both the lateral directions of the micro bridge mechanism model with the assumption that the neutral axis was located at the centroid of the nickel layer. A summary of the z-deflection results for each micro bridge mechanism is listed in Table 5.3. From Table 5.3, Prototype A4 (Figure 5.7) and Prototype A5 produced the largest deflections for each micro bridge mechanism type.

Table 5.3 Simulated micro bridge mechanism z-deflection results.

Prototype	Spring Type	Spring Width (μm)	Support Beam Width (μm)	Maximum z-deflection (μm)	Minimum z-deflection (μm)
A1	Squared	10	8	58.5	-16.6
A4		8	8	65.8	-17.7
B1, B3, B4		10	10	48.8	-15.5
C1		10	10	52.9	-15.5
A2	Curved	10	10	47.6	-15.2
A3		10	8	56.6	-16.1
A5		8	8	63.7	-17.1
B2, B5		10	10	47.6	-15.2

Figure 5.7 3D deflection profile of Prototype A4.

From Table 5.3, the squared serpentine spring micro bridge mechanisms have a slightly higher deflection than the curved serpentine spring micro bridge mechanisms. This outcome is due to the squared serpentine springs having a stiffer structure than the curved serpentine springs and the double cantilever beams having a longer length than the double cantilever beams of the curved serpentine spring bridge mechanism. A longer double cantilever beam will deflect more downward due to the residual stress gradient in the nickel layer. Another factor contributing to the deflection is the width of the spring and support beams. The width is smaller than the total three layer metal thickness by a factor greater than two. According to the results in Table 5.3, the micro bridge mechanisms that have an $8 \mu\text{m}$ wide spring and support beam deflected higher than the micro bridge mechanism that have a $10 \mu\text{m}$ wide spring and support beam.

5.3 Analytical model to determine the maximum deflection

The analytical model to determine the maximum deflection of the tip of the free cantilever of the micro bridge mechanism assumes that:

1. The bending moment caused by the residual mean tensile stress in the nickel layer due to the asymmetrical structure of the composite beam is neglected.
2. The residual stresses in both the gold and copper layers are neglected due to their small thickness in comparison to the nickel layer.
3. The resisting moment from the twisting of the support beams (SB) is minute and does not significantly affect the downward deflection of the double cantilever beams.
4. The two types of springs act as plain connectors between the parts and have minimal distortions.
5. The bending moment of the composite beam is only induced by the residual stress gradient in the nickel layer.
6. The double cantilever beam (DCB) is simplified to a fixed-free cantilever beam.
7. The double bridge beam (DBB) is simplified to a beam which is simply supported at both ends.

The deflection of the double cantilever beam can be equated to a concentrated moment at the free end of the beam. As shown in Figure 5.8, the deflection of the double cantilever beam is calculated by [95][109]:

$$\delta_A = \frac{\Gamma L_{DCB}^2}{2C_1} \quad (5.1)$$

where δ_A is the deflection of the double cantilever beam, Γ is the residual stress gradient of the nickel layer, L_{DCB} is the length of the double cantilever beam and C_1 is a constant determined by

dividing the equivalent bending rigidity of the three layered composite cross-section by the second moment of inertia of the nickel layer in the composite.

Figure 5.8 Deflection of the double cantilever beam.

The constant C_1 is determined by [109]:

$$C_1 = \frac{\tilde{E}_{Ni} I_{Ni} + \tilde{E}_{Cu} I_{Cu} + \tilde{E}_{Au} I_{Au}}{I_{Ni}} \quad (5.2)$$

where I_{Ni} , I_{Cu} , I_{Au} are the second moment of inertia of the nickel, copper and gold layers about the neutral axis (see Figure 4.17) for a rectangular cross-section, respectively. $\tilde{E}_{Ni}$, $\tilde{E}_{Cu}$, $\tilde{E}_{Au}$ are the equivalent effective Young's modulus of the nickel, copper and gold layers, respectively, and are calculated by equation (3.7). Figure 5.9 shows the labelled parts of the micro bridge mechanism used in the subsequent deflection calculations. In Figure 5.9, L_A is the length from point A to point B, L_B is the length from point B to point C, L_{FC} is the length of the free cantilever, L_{SB} is the length of the support beam, and L_{DBB} is the length of the double bridge beam. The dimensions of each length in Figure 5.9 for each micro bridge mechanism are listed in Table 5.4. A diagram of showing the variables used to determine of the maximum deflection of the free cantilever of the micro bridge mechanism is shown in Figure 5.10. The formulas of each variable used to determine of the maximum deflection of the micro bridge mechanism are summarized in Table 5.5.

Figure 5.9 Lengths of the micro bridge mechanism used in the deflection calculations.

Table 5.4 Dimensions of the lengths shown in Figure 5.9.

Prototype	Spring Type	L_{DCB} (μm)	L_{DBB} (μm)	L_{SB} (μm)	L_A (μm)	L_B (μm)	L_{FC} (μm)
A1	Squared	1500	2220	500	450	140	860
A4		1500	2220	500	446	140	864
B1, B3, B4		1500	2120	550	450	140	860
C1		1500	2120	550	450	140	995
A2	Curved	1430	2120	550	450	140	860
A3		1430	2220	500	450	140	860
A5		1438	2220	500	436	140	874
B2, B5		1430	2120	550	450	140	860

Figure 5.10 Variables used in determining the maximum deflection of the micro bridge mechanism.

Table 5.5 Formulas used for each variable in determining maximum deflection of the micro bridge mechanism.

Variable	Equation [95][109]	Description	Equation No.
δ_A	$= \frac{\Gamma L_{DCB}^2}{2C_1} k_1$	Deflection at point A caused by the residual stress gradient in the DCB. k_1 is a multiplication factor that depends on the width of the spring.	(5.1)
C_1	$= \frac{\tilde{E}_{Ni} I_{Ni} + \tilde{E}_{Cu} I_{Cu} + \tilde{E}_{Au} I_{Au}}{I_{Ni}}$	A constant determined by dividing the equivalent bending rigidity of the composite cross-section by the second moment of inertia of the nickel layer in the composite.	(5.2)
δ_1	$= -\frac{\Gamma L_{DBB}^2}{8C_1} + \frac{\Gamma L_{SB}^2}{C_1} k_2$	Raised deflection of point B caused by the residual stress gradient in the DBB and SB. k_2 is a multiplication factor that depends on the width of the support beam.	(5.3)
δ_2	$= -\delta_A + \delta_1$	Deflection of point A relative to point B.	(5.4)
θ_B	$= \sin^{-1} \left(\frac{\delta_2}{L_A} \right)$	Angle generated by δ_A	(5.5)
δ_3	$= \left(\frac{L_B}{L_A} \right) \delta_2$	Deflection of point C.	(5.6)
θ_{FC}	$= \frac{\Gamma L_{FC}}{C_1}$	Angle of rotation of the deflected free cantilever.	(5.7)
θ_C	$= \theta_B + \theta_{FC}$	Angle of the deflected free cantilever from the horizontal plane.	(5.8)
δ_4	$= L_{FC} \sin \theta_C$	Vertical deflection of the free cantilever.	(5.9)
δ_{max}	$= \delta_4 + \delta_3 + \delta_1$	Maximum deflection of the micro bridge mechanism.	(5.10)

The multiplication factors for the springs and support beams are listed in Table 5.6 and were based on the conducted numerical simulations of the micro bridge mechanisms in Section 5.2. Therefore, the maximum deflection, δ_{max} , of the micro bridge mechanism is determined by equation (5.10).

Using the nominal thicknesses from Table 4.1, the material properties from Table 4.2 with the Young's modulus of 159 GPa for the nickel layer, and the average residual stress gradient of -4.72 MPa/ μ m from Section 4.2.3, calculations of the typical deflection of each micro bridge mechanism were conducted using equation (5.10). C_1 was calculated via equation (5.2) as

251.4 GPa, since all the cross-sections have a constant width. The results of the calculated typical deflection of each micro bridge mechanism are listed in Table 5.6.

Table 5.6 Typical deflections of the micro bridge mechanism calculated using equation (5.10).

Prototype	Spring Type	Spring Width (μm)	k_1	Support Beam Width (μm)	k_2	δ_{final} (μm)
A1	Squared	10	1	8	0.8	58.24
A4		8	1.14	8	0.8	65.61
B1, B3, B4		10	1	10	1	48.75
C1		10	1	10	1	51.85
A2	Curved	10	1.07	10	1	47.46
A3		10	1.07	8	0.8	56.94
A5		8	1.14	8	0.8	63.12
B2, B5		10	1.07	10	1	47.46

The analytical model provides a reasonable estimate of the deflections in Table 5.6 to within 3% of the simulated deflection results from Table 5.3. This difference is because the analytical model does not take into account of the stiffness in the springs and the support beams and the non-ideal boundary support of the anchor pads.

5.4 Measured deflections of the fabricated micro bridge mechanisms

The maximum deflection of the free cantilever of each fabricated micro bridge mechanism on two MetalMUMPs[®] loose dies was measured under the Zygo[®] optical interferometer using the MetroPro Films Application. The surface profile of each fabricated micro bridge mechanism was scanned with the 20X objective lens with the 0.5X internal magnification of the scope. The maximum deflection of the free cantilever of the bridge mechanism was obtained by subtracting the measured depth of the substrate trench from the measured vertical height of the free cantilever. The vertical height of the free cantilever was measured from the tip of the free cantilever to the surface of the substrate trench and is shown in Figure 5.11 using a slice line in the MetroPro Films application. The depth of the substrate trench

was measured from the bottom surface of the trench to the top surface of the Nitride 2 layer at the edge of the trench.

All the maximum deflections are summarized in Table 5.7 for all the fabricated micro bridge mechanism prototypes on loose die 1 and loose die 2. Measurements for each micro bridge mechanism are listed in Appendix C. The measured maximum deflections of the micro bridge mechanisms indicated by an asterisk in Table 5.7 were affected by the attached silicon nitride beams sticking to the surface of the substrate trench, which inhibited the complete release of the micro bridge mechanisms. However, from Table 5.7, many of the unaffected micro bridge mechanisms have maximum deflections that are close to the deflections obtained in Table 5.3 and Table 5.6.

Figure 5.11 Measuring the vertical height from the tip of the free cantilever to the surface of the substrate trench.

Table 5.7 Measured maximum deflections of the eleven micro bridge mechanisms.

Prototype	Spring Type	Maximum deflection (μm)	
		Loose die 1	Loose die 2
A1	Squared	59.02	53.93
A4		68.48	73.85
B1		*24.82	*20.16
B3		55.68	*24.59
B4		60.28	*25.59
C1		52.04	*34.68
A2	Curved	55.49	62.84
A3		58.58	66.47
A5		59.73	63.32
B2		52.45	*32.45
B5		52.97	*24.87

*Affected by the attached silicon nitride beams.

5.5 Calculated deflections of the fabricated micro bridge mechanisms

In this section, the deflection of each fabricated micro bridge mechanism is calculated by using equation (5.10) and conducting numerical simulations. The nickel thickness of each fabricated micro bridge mechanism is measured in Section 5.5.1 and the residual stress gradient of the nickel layer is extracted using the free beam of the Prototype C1 micro bridge mechanism in Section 5.5.2. Both the measured thicknesses and extracted values of the residual stress gradient of the nickel layer are used for calculating the deflection for each fabricated micro bridge mechanism in Section 5.5.3. A comparison of the measured and calculated deflections is also discussed in Section 5.5.3.

5.5.1 Nickel thickness measurements for each micro bridge mechanism

The thickness of the nickel layer was measured near the anchor pads of each double cantilever beam along the line C-C as shown in Figure 5.12 for each micro bridge mechanism using the MetroPro Films Application. The nickel thickness was obtained by subtracting the nominal thickness of the copper and gold layers (Table 4.1) from the measured composite

thickness. The average and standard deviation (σ_p via equation (2.1) of the nickel thickness measurements are listed in Table 5.8 for each micro bridge mechanism on loose die 1 and loose die 2. The measurements of the composite thickness are listed in Appendix C.

Figure 5.12 Thickness measurement location for the micro bridge mechanism.

Table 5.8 Measured nickel thickness for each micro bridge mechanism on each loose die.

Prototype	Spring Type	Loose die 1 (μm)	Loose die 2 (μm)
A1	Squared	19.43 ± 0.83	20.03 ± 1.00
A4		21.59 ± 0.44	20.55 ± 2.12
B1		19.65 ± 0.50	19.41 ± 0.02
B3		21.12 ± 0.51	20.15 ± 0.62
B4		21.35 ± 0.99	20.34 ± 0.33
C1		20.80 ± 1.20	19.05 ± 0.27
A2	Curved	20.71 ± 0.31	19.92 ± 0.92
A3		21.38 ± 0.07	19.82 ± 0.95
A5		22.42 ± 0.64	20.18 ± 1.30
B2		20.43 ± 0.42	19.93 ± 0.89
B5		21.99 ± 0.71	20.45 ± 0.02

5.5.2 Residual stress gradient extraction of the nickel layer

The Prototype C1 micro bridge mechanism has a free beam attached to the end of its free cantilever as shown in Figure 5.6. Using the approach in Section 4.2, the residual stress gradient of the nickel layer was extracted by measuring the curvature of the free beam of the Prototype C1 micro bridge mechanism on loose die 1 and loose die 2. The surface profile of each free beam

was scanned using the MetroPro Films Application of Zygo[®] optical interferometer. Three slice lines were drawn within the surface profile of the free beam and the radius of curvature for each slice line was obtained automatically with the built in “RadCrv” feature of the application and listed in Table 5.9. The three slice lines in the surface profile are shown in Figure 5.13 and the average of the three measurements listed in Table 5.9 was used to obtain the residual stress gradient of the nickel layer for each loose die.

Figure 5.13 Slice line measurement locations on the free beam.

Table 5.9 Radius of curvature measurements of the free beam

	Radius of Curvature (μm)	
	Loose die 1	Loose die 2
Slice #1	47235.0	47065.4
Slice #2	47354.2	46984.5
Slice #3	47694.2	46829.7
Average	47428	46960

The residual stress gradient of the nickel layer was calculated via equation (4.4) by using the measured nickel thickness of the Prototype C1 micro bridge mechanism from Table 5.8, the nominal thickness of the copper and gold layers from Table 4.1, and the material properties from Table 4.2 with the Young’s modulus of 159 GPa for the nickel layer. The calculated results of the residual stress gradient of nickel film and the residual stress change across the nickel thickness are listed in Table 5.10 for loose die 1 and loose die 2.

Table 5.10 Extracted results of the residual stress gradient.

Loose die no.	Residual stress gradient (MPa/ μm)	Residual stress change across the thickness (MPa)
1	-5.28	-109.84
2	-5.38	-102.51

5.5.3 Calculated deflection results

Using the measured nickel thicknesses from Table 5.8, the nominal copper and gold thicknesses from Table 4.1, the mechanical properties of Table 4.2 with the Young's modulus of 159 GPa for the nickel layer, the lengths from Table 5.4, the multiplication factors from Table 5.6, and the extracted values of the residual stress gradient from Table 5.10, the maximum deflection of each fabricated micro bridge mechanism was determined via equation (5.10) of the analytical model for loose die 1 and loose die 2, and are summarized in Table 5.11.

Using the same procedure to simulate the micro bridge mechanisms in Section 5.2, the maximum deflections of each fabricated micro bridge mechanism were simulated in CoventorWareTM [69]. Each micro bridge mechanism model was built using the dimensions given in Table 5.1 and Table 5.2, the measured nickel thicknesses from Table 5.8 and the nominal copper and gold thicknesses from Table 4.1. The models were fixed at their four anchor pads and were meshed using 10-node Tetrahedrons since the thickness of the copper and gold layers were very thin in comparison to the thick nickel layer. Tetrahedrons with various element sizes were tested and it was found that an element size of 19 μm was sufficient to obtain accurate results. The models used the material properties from Table 4.2 with the Young's modulus of 159 GPa for the nickel layer and the extracted results of the residual stress gradient from Table 5.10. The residual stress gradient was applied in both the lateral directions of the micro bridge mechanism model with the assumption that the neutral axis was located at the centroid of the

nickel layer. The simulation deflection results of each micro bridge mechanism are summarized in Table 5.11.

Table 5.11 Summary of the calculated and measured deflections of each fabricated micro bridge mechanism on loose die 1 and loose die 2.

Loose die No.	Prototype	Spring Type	Maximum deflection (μm)			% Diff.
			Measured	Analytical Model	Numerical Simulation	
1	A1	Squared	59.02	64.96	63.89	8
	A4		68.48	73.95	78.03	14
	B1		*24.82	54.44	53.72	116
	B3		55.68	54.83	57.45	3
	B4		60.28	54.89	57.99	-4
	C1	Curved	52.04	58.24	61.42	18
	A2		55.49	53.28	54.77	-1
	A3		58.58	64.13	66.49	14
	A5		59.73	71.40	76.94	29
	B2		52.45	53.21	54.20	3
	B5		52.97	53.58	57.57	9
2	A1	Squared	53.93	66.40	66.78	24
	A4		73.85	74.99	76.64	4
	B1		*20.16	55.40	54.11	168
	B3		*24.59	55.62	56.02	128
	B4		*25.59	55.67	56.48	121
	C1	Curved	*34.68	58.81	57.57	66
	A2		62.84	54.08	54.01	-14
	A3		66.47	64.85	64.08	-4
	A5		63.32	72.02	73.06	15
	B2		*32.45	54.08	54.11	67
	B5		*24.87	54.22	55.27	122

*Affected by the attached silicon nitride beams.

Although several of the fabricated micro bridge mechanisms were affected by the attached silicon nitride beams, the maximum deflections of the fabricated micro bridge mechanisms calculated by equation (5.10) of the analytical model and determined by numerical simulation in Table 5.11 closely match the measured deflections of the fabricated micro bridge mechanisms on each loose die. The fabricated micro bridge mechanisms deflected at least $50 \mu\text{m}$

without being affected by the attached silicon nitride beams. From Table 5.11, the calculated deflections (analytical and simulated) differ as low as 1% but as high as 168% compared to the measured deflections. The difference between the calculated deflections and measured deflections of each fabricated micro bridge mechanism not affected by silicon nitride beams can be attributed to the out-of-plane rotation of the whole bridge mechanism that might be caused by the inertial moment generated during the rinsing and drying stages of the fabrication process, which might induce plastic deformation in the serpentine springs and support beams. This plastic deformation in the serpentine springs and support beams may result in a higher or lower measured deflection of the fabricated micro bridge mechanisms than the calculated deflections.

5.6 Summary

Deflection measurements of the micro bridge mechanisms found that the micro bridge mechanisms with high deflections included: narrow support beams, long double cantilevers beams and narrow squared serpentine springs in its design. The largest deflection measured for the fabricated micro bridge mechanisms was $73.85\text{ }\mu\text{m}$ (from Table 5.11), which shows that silicon nitride beams attached to the micro bridge mechanism can be suspended successfully by utilizing the negative residual gradient in the nickel film to deflect out-of-plane the free cantilever of the micro bridge mechanism. Therefore, the design of the micro bridge mechanism can also be used for lifting and suspending micro structures made of other films above the substrate.

Chapter 6 Conclusions and Recommendations for Future Work

The properties of the MetalMUMPs[®] silicon nitride and nickel thin films were measured in this thesis. A Young's modulus of 209 GPa of the silicon nitride films was extracted using the resonance method. A residual stress difference of 169 MPa of the two silicon nitride films was determined through the proposed method, which uses the radii of curvature along the width of silicon nitride bi-layered cantilever beams. A Young's modulus of 159 GPa was obtained for the nickel film also using the resonance method and a negative residual stress gradient of -4.72 MPa/ μm of the nickel film was extracted using the curvature of free beams. Lastly, the design of the micro bridge mechanism was presented and the largest out-of-plane deflection 73.85 μm was measured for the fabricated micro bridge mechanisms.

The Young's modulus and the residual stress difference of the silicon nitride films, the Young's modulus and the residual stress gradient of the nickel films obtained in this thesis provide MetalMUMPs[®] users an important reference of property measurement data in designing, analyzing and optimizing MetalMUMPs[®] devices.

The following recommendations are suggested for future designs of fabricating micro structures for property measurement or for micro devices fabricated using the MetalMUMPs[®] process:

- The silicon nitride cantilever beams (one or two layer) that are suspended over the substrate trench should not exceed 500 μm in length in order to reduce the number of failures of having the beams sticking to the substrate trench.
- Design a silicon nitride bridge beam (i.e., a beam that is fixed at both ends) with a trench below it and have a bridge made of the anchor metal layer placed on top of the silicon nitride

bridge and fixed to the silicon nitride layer (see Figure 6.1). This allows for easier thickness measurement of the two combined silicon nitride layers.

Figure 6.1 Layout for easier thickness measurement for the two combined silicon nitride layers.

- The silicon nitride cantilever beam lengths should have increments as small as $10\text{ }\mu\text{m}$, so a larger range of the resonant frequencies is used for extracting the Young's modulus.
- Do not use Oxide 1 to define the trench under the silicon nitride cantilever beams. Instead, define trench with the "NITRHOLE" layer. A small trench should form since the isolation oxide layer is exposed during the KOH etch in the fabrication process.
- Design bi-layered silicon nitride beams to have beam widths ranging from $25\text{ }\mu\text{m}$ to $200\text{ }\mu\text{m}$ to extract more values of the residual stress difference of the two silicon nitride films.
- Do not have the silicon nitride beams that are attached to the free cantilever of the micro bridge mechanism to exceed $500\text{ }\mu\text{m}$ in length to reduce the possibility of the silicon nitride beams sticking to the substrate trench and affecting the deflection of the micro bridge mechanism.

Appendix A Procedures

A.1 General setup procedure for the Zygo® optical interferometer

Details of setting up the Zygo® optical interferometer and its operation and using its applications can be found in the reference manuals [59]-[61][65]. General setup instructions are given here.

1. Place the loose die or micro object on the stage under the Zygo® objective and power on the Zygo® optical interferometer.
 - a. If conducting a dynamic test, turn on the function generator prior to turning on the power to the Zygo® optical interferometer. Ensure the voltage amplifier is turned off.
2. Adjust the stage on the Zygo® scope to the desired location on the chip to be measured.
3. Start MetroPro and open the Films Application or the Dynamics Application.
 - a. If conducting a dynamic test, the Zygo® system will automatically connect and control the function generator once the Dynamics Application is opened.
4. In the Measure Ctrl window, set the following as desired:
 - a. Zoom magnification: 0.5X, 1X, 2X
 - b. Scanning length (μm): 5, 10, 15, 20, 40, 100, 150
5. Focus the scope's camera by adjusting the Z direction of the scope and find the dark fringes on a flat metallic surface on the chip or loose die (adjust the speed and lighting as necessary).
6. Null the fringes and adjust the lighting in the scope to remove the red saturation levels. To do this automatically by the machine, hit the function key F5. To adjust the lighting manually, hit the function key F4 and adjust the lighting with the “/” or “*” keys for large steps or the “-” or “+” for small steps.
7. Adjust the stage to the desired micro structure's location and measure the structure for its surface profile either by clicking on the “Measure” button or hit the function key F1.
8. Proceed with measuring other locations of interest or use the dynamic functions of the interferometer. Below are some tips in using the software.
 - a. In the (top) surface profile window, a slice line can be created within the pixel image of the desired location to be measured by left clicking and dragging with

the mouse. From the profile plot window, observe that a plot of the slice is generated.

- b. A profile plot of the measurement can be saved as an Excel file for subsequent calculations or for graphs by clicking on the “Zygo” logo on the top left corner of the profile plot window. A window will pop up (see Figure A.1), click on “Data” in the source column, then “File” in the destination column, “Tabs” in the data format column and lastly click “Print”. Save the name with the “.xls” extension.
- c. Also an image of the profile plot or any other window in the application can be saved as an image by clicking on the “Zygo” logo on the top left corner of the window.
- d. “Inspector” lines in the profile plot window may be used to measure the X and Y distances between the two inspector lines. The “Inspector” lines are enabled from the “plot controls” of the profile plot window (click on the “Inspect Off” button).
- e. Profile plots can be “levelled” by using the “Level” button in the “plot controls” of the profile plot window. This feature can be used when the measured profile of the micro structure’s adjacent flat surfaces are higher or lower relative to each other.
- f. Take note that the Zygo[®] optical interferometer measures the top surface of the film.

Figure A.1: Saving data to a file.

Appendix B Technical Drawings and Layouts

B.1 Poly trench drawing

B.2 Mask layouts

Mask layout for the silicon nitride bi-layered cantilever beam

Mask layout for the single layer silicon nitride cantilever beam

Mask layout for the nitride-polysilicon-nitride cantilever beam

B.3 Piezoelectric transducer part drawings

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				DRAWN			
				CHECKED			
				ENG APPR.			
				MFG APPR.			
		MATERIAL	Q.A.		COMMENTS:	SIZE DWG. NO. REV. A	
NEXT ASSY	USED ON	FINISH					
APPLICATION		DO NOT SCALE DRAWING					
				SCALE: 1:1	WEIGHT:		SHEET 1 OF 1

B.4 Micro bridge mechanism part drawings

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				DRAWN			
				CHECKED			
				ENG APPR.			
				MFG APPR.			
NEXT ASSY		USED ON		MATERIAL		Q.A.	
APPLICATION		DO NOT SCALE DRAWING		FINISH		COMMENTS	
				SIZE		DWG. NO.	
				SCALE: 500:1		WEIGHT:	
						SHEET 1 OF 1

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		DRAWN				
		CHECKED				
		ENG APPR.				
		MFG APPR.				
NEXT ASSY		USED ON	FINISH	COMMENTS:		
APPLICATION		DO NOT SCALE DRAWING				
				SEP	DWG. NO.	REV.
				A	SCALE: 200:1	WEIGHT:
						SHEET 1 OF 1

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				DRAWN		
				CHECKED		
				ENG. APPR.		
				MFG. APPR.		
MATERIAL		G.A.		COMMENTS		
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				
				SIZE A	DWG. NO.	REV.
				SCALE: 300:1	WEIGHT:	SHEET 1 OF 1

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				DRAWN		
				CHECKED		
				ENG. APPR.		
				MFG. APPR.		
		MATERIAL		Q.A.		COMMENTS:
		FINISH				
NEXT ASSY		USED ON		SCALE: 100:1		SIZE A DWG. NO. SHEET 1 OF 1
APPLICATION		DO NOT SCALE DRAWING		WEIGHT:		REV.

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				DRAWN		
				CHECKED		
				ENG APPR.		
				MFG APPR.		
MATERIAL		QA		COMMENTS		
FINISH						
APPLICATION		DO NOT SCALE DRAWING				
NEXT ASSY	USED ON			SIZE	DWG. NO.	REV.
				A		
				SCALE: 1:100	WEIGHT:	SHEET 1 OF 1

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				DRAWN		
				CHECKED		
				ENG APPR.		
				MFG APPR.		
		MATERIAL		Q.L.A.		
		FINISH		COMMENTS:		
NEXT ASSY	USED ON					
APPLICATION		DO NOT SCALE DRAWING				
				SIZE DWG. NO.		REV.
				A		
				SCALE: 50:1 WEIGHT		SHEET 1 OF 1

Beam Length (µm)	Resonant Frequency 1 (Hz)	Resonant Frequency 2 (Hz)	Mode
100	4130	42200	1 st
150	38700	18800	1 st
150			

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				CHECKED			
				ENG APPR.			
				MFG APPR.			
				QA			
		MATERIAL		COMMENTS			
NEXT ASSY	USED ON	FINISH					
APPLICATION		DO NOT SCALE DRAWING					
				SIZE DWG. NO. A		REV.	
				SCALE: 50:1		SHEET 1 OF 1	

Appendix C Experimental Measurement Data

C.1 Thickness measurements of the two silicon nitride and polysilicon layers on loose die 1 and loose die 2

Table C.1 Thickness measurements on loose die 1.

Loose die 1			
Measurement location no.	Nitride 2 thickness (μm)	Combined silicon nitride thickness (μm)	Polysilicon thickness (μm)
1	0.252	0.568	0.705
2	0.252	0.568	0.697
3	0.250	0.573	0.683
4	0.251	0.563	0.689
5	0.250	0.572	0.710
6	0.250	0.572	0.674
7	0.248	0.564	0.676
8	0.249	0.566	0.693
9	0.252	0.569	0.701
10	0.251	0.572	0.705
11	0.247	0.568	0.692
12	0.248	0.572	0.693
13	0.252	0.586	0.693
14	0.252	0.570	0.695
15	0.251	0.572	0.685
16	0.250	0.571	0.701
17	0.247	0.571	0.672
18	0.248	0.570	0.679
19	0.251	0.572	0.691
20	0.250	0.585	0.696
Average (μm)	0.250	0.571	0.691
Standard Deviation (μm)	0.002	0.006	0.011

Table C.2 Thickness measurements on loose die 2.

Loose die 2				
Measurement location no.	Nitride 2 thickness (μm)	Combined silicon nitride thickness (μm)	Polysilicon thickness (μm)	Nitride 1 thickness (measured on the substrate trench) (μm)
1	0.260	0.578	0.707	0.323
2	0.259	0.592	0.698	0.323
3	0.262	0.583	0.733	0.322
4	0.262	0.582	0.675	0.327
5	0.254	0.601	0.692	0.322
6	0.254	0.582	0.709	0.323
7	0.256	0.593	0.691	0.325
8	0.255	0.581	0.701	0.325
9	0.257	0.584	0.702	0.320
10	0.258	0.585	0.680	0.320
11	0.259	0.584	0.701	0.322
12	0.258	0.581	0.686	0.323
13	0.261	0.598	0.674	0.321
14	0.261	0.582	0.677	0.329
15	0.258	0.582	0.679	0.311
16	0.258	0.582	0.688	0.325
17	0.256	0.580	0.687	0.326
18	0.256	0.579	0.699	0.329
19	0.259	0.579	0.699	0.324
20	0.260	0.579	0.688	0.328
Average (μm)	0.258	0.584	0.693	0.323
Standard Deviation (μm)	0.003	0.006	0.014	0.004

C.2 Resonant frequency measurements of the single layer silicon nitride cantilever beams

Table C.3 Measured resonant frequencies of the single layer silicon nitride cantilever beams.

Beam Length (μm)	Resonant Frequency (Hz)		
	Loose die 1	Loose die 2	Mode
100	41300	42200	1 st
150	18300	18800	1 st
150	18300	18700	1 st
200	n/a	66800	2 nd
200	66700	66700	2 nd
250	n/a	43100	2 nd
250	n/a	43200	2 nd
300	n/a	30000	2 nd
300	n/a	30100	2 nd

C.3 Extracted Young's modulus of the silicon nitride films via numerical simulations

Table C.4 Extracted Young's modulus results for the silicon nitride films via numerical simulations.

Beam Length (μm)	Young's modulus (GPa)		
	Loose die 1	Loose die 2	Mode
100	209	215	1 st
150	201	210	1 st
150	201	208	1 st
200	n/a	210	2 nd
200	212	209	2 nd
250	n/a	211	2 nd
250	n/a	212	2 nd
300	n/a	211	2 nd
300	n/a	212	2 nd

C.4 Radius of curvature along the beam width measurements of the silicon nitride bi-layered cantilever beams on loose die 1

Table C.5 Radius of curvature along the beam width measurements for the 25 wide bi-layered beams.

Measurement No./Beam Length	Measured R_w for the 25 μm wide beams			
	400 μm	450 μm	500 μm	550 μm
1	573.44	578.96	592.68	581.45
2	572.61	578.14	582.20	577.05
3	570.76	576.50	586.61	573.30
4	569.58	572.57	589.51	572.97
5	567.59	575.81	582.24	571.36
6	568.15	579.18	576.24	568.98
7	566.02	573.59	575.92	569.93
8	566.34	567.33	569.13	568.24
9	565.89	570.42	570.46	568.28
10	563.73	568.21	572.31	566.41
11	564.09	568.34	575.86	565.66
12	565.45	571.58	572.38	570.45
13	564.60	573.96	582.07	567.75
14	563.70	576.63	576.96	569.43
15	566.75	574.82	575.87	571.45
16	562.87	570.51	578.98	570.79
17	558.30	574.63	587.20	572.04
18	541.49	577.65	581.07	570.75
19	554.38	567.49	576.02	568.86
20	563.51	568.25	580.41	569.91
21	565.37	571.49	577.51	567.85
22	564.86	574.11	582.26	565.98
23	568.18	567.04	579.53	568.81
24	570.83	570.59	575.51	568.31

25	568.38	570.24	576.05	565.82
26	569.09	572.65	574.55	570.78
27	564.36	571.29	577.40	567.13
28	565.71	573.07	579.47	567.65
29	565.14	574.16	572.89	566.38
30	565.24	571.68	578.96	564.85
31	568.83	574.64	577.37	566.80
32	564.20	574.71	581.97	568.29
33	566.83	574.77	574.08	573.80
34	567.59	572.22	578.10	575.60
35	569.29	573.84	578.65	574.70
36	569.39	573.39	578.83	573.06
37	567.92	573.74	580.31	576.54
38	572.45	566.88	584.05	576.63
39	564.66	569.23	576.86	575.55
40	567.46	571.00	575.00	572.07
41	568.98	570.67	585.90	575.88
42	562.99	570.18	577.08	572.35
43	568.40	569.90	583.07	577.02
44	565.03	573.32	582.64	575.82
45	567.39	573.57	578.95	574.13
46	565.38	571.75	581.28	573.29
47	566.79	567.11	580.69	577.55
48	561.28	570.52	578.86	574.25
49	561.30	575.93	579.21	577.06
50	565.50	570.03	577.48	578.95
51	560.84	568.99	581.93	572.49
52	563.54	570.59	576.44	574.39
53	566.15	570.47	577.08	577.57
54	563.01	574.43	578.51	578.16
55	562.37	571.48	582.99	576.95
56	563.66	572.62	577.21	574.86
57	564.84	573.85	582.78	579.21
58	563.85	571.96	580.72	580.13
59	567.58	567.22	582.75	578.03
60	564.91	569.68	583.93	581.78
61	567.74	573.38	584.76	577.08
62	568.98	570.64	584.16	578.63
63	570.38	568.03	582.52	582.02
64	567.79	572.75	582.60	579.54
65	567.33	573.07	584.03	580.52
66	566.63	570.97	581.19	579.98
67	570.47	570.92	578.93	577.65
68	572.07	571.88	577.53	577.07
69	568.17	572.84	582.73	576.67
70	570.31	573.94	581.92	578.39
71	568.24	575.07	581.40	574.58
72	568.14	569.98	583.83	572.57
73	571.51	572.02	582.89	573.12
74	570.95	572.66	583.72	571.96
75	573.72	574.36	585.88	576.45
76	572.09	572.60	582.63	573.60
77	568.68	575.72	583.51	571.69

78	570.16	570.91	585.37	573.81
79	572.23	566.71	585.04	575.38
80	569.62	570.47	586.47	576.13
81	576.27	569.05	583.98	576.15
82	572.36	568.54	585.32	579.31
83	566.62	574.49	584.02	575.56
84	566.39	572.58	588.31	580.12
85	569.49	569.55	587.95	578.59
86	570.19	573.98	586.36	583.61
87	567.11	571.92	587.75	578.69
88	570.66	572.95	584.58	583.31
89	570.16	568.66	585.86	578.71
90	571.80	573.98	586.69	578.97
91	577.20	570.30	587.96	577.68
92	571.65	570.44	585.42	574.51
93	572.82	571.97	587.47	577.00
94	575.80	573.92	582.84	582.45
95	575.53	576.77	591.11	577.99
96	575.67	574.62	585.52	577.03
97	579.16	576.20	582.19	577.75
98	576.24	574.05	589.29	583.32
99		575.86	583.37	580.78
100		575.91	584.37	579.00
101		578.10	587.90	578.16
102		573.39	587.13	577.58
103		573.50	587.35	575.91
104		580.18	589.86	580.93
105		576.32	592.73	577.82
106		578.07	589.34	577.50
107		578.26	588.26	577.54
108		579.09	589.40	581.43
109		580.55	590.09	581.19
110		578.41	594.31	580.23
111		581.54	592.52	582.89
112			595.92	576.33
113			591.67	577.05
114			592.39	577.01
115			592.29	576.78
116			592.86	579.26
117			598.36	578.22
118			592.59	579.38
119			593.78	577.83
120			596.02	583.53
121			591.88	579.05
122			593.67	585.88
123			596.39	582.58
124			597.74	582.96
125			597.67	581.94
126			597.12	577.69
127			596.22	585.02
128				580.49
129				582.77
130				581.63

131				580.61
132				580.91
133				582.53
134				584.65
135				586.98
136				583.85
137				583.59
138				585.44
139				583.06
140				585.78
141				584.40
142				583.44
143				580.54
144				583.69
145				587.07
146				587.10
147				591.15
148				591.98
149				588.31
150				585.35
151				587.72
152				589.32
153				590.89
154				589.38
155				589.32
156				586.52
157				591.02
158				585.43
159				588.72

Table C.6 Radius of curvature along the beam width measurements for the 50 wide bi-layered beams.

Measurement No./Beam Length	Measured R_w for the 50 μm wide beams				
	500 μm	550 μm	600 μm	650 μm	700 μm
1	671.50	674.30	671.83	672.59	669.07
2	669.51	672.07	670.05	671.68	668.59
3	668.04	669.06	667.56	670.52	666.91
4	664.82	666.78	665.33	669.84	665.05
5	663.34	666.28	666.14	669.62	663.22
6	661.51	665.26	663.63	667.15	663.92
7	660.97	663.69	664.28	667.66	663.03
8	659.65	663.97	664.36	662.93	663.42
9	660.14	663.57	665.07	665.23	662.08
10	659.02	662.27	663.19	662.71	661.73
11	659.42	660.15	662.26	661.81	661.20
12	659.55	661.01	661.47	660.93	660.06
13	657.78	662.19	662.41	660.86	660.58
14	659.54	661.85	661.35	660.96	660.73
15	658.83	662.37	662.04	659.74	660.16
16	658.21	662.73	661.14	660.26	660.17
17	657.63	661.46	662.30	660.12	659.01
18	658.60	662.64	661.02	659.37	660.32

19	657.31	662.48	661.08	660.11	660.06
20	658.68	662.87	659.82	659.84	659.69
21	660.12	661.87	659.77	660.66	659.50
22	660.67	662.06	660.48	660.89	660.47
23	660.67	661.17	659.47	658.75	662.62
24	661.32	661.88	660.21	658.19	660.32
25	661.09	660.89	658.54	659.21	660.82
26	661.08	660.73	659.42	659.08	661.26
27	661.51	661.09	658.84	659.72	658.99
28	661.04	659.90	660.13	659.43	660.52
29	662.28	659.74	658.72	660.13	658.52
30	660.70	660.04	659.74	659.79	658.65
31	661.58	659.83	659.10	660.45	658.95
32	660.52	658.52	659.10	658.90	658.83
33	660.10	659.06	659.69	658.84	659.68
34	660.46	658.20	659.52	659.24	659.91
35	659.78	659.18	659.61	659.70	658.59
36	659.26	660.44	659.47	657.61	657.31
37	659.48	660.63	659.56	658.11	658.25
38	659.67	659.84	658.65	658.27	657.73
39	660.46	661.72	659.89	656.95	659.95
40	661.80	661.96	658.54	657.63	658.60
41	661.20	661.00	658.68	657.65	657.87
42	662.36	660.54	658.47	657.49	658.09
43	662.46	662.50	658.94	657.43	658.69
44	662.24	661.71	659.11	658.10	656.67
45	662.97	663.10	658.56	657.56	658.66
46	663.19	664.00	658.17	657.90	658.13
47	663.13	664.95	659.52	659.75	657.86
48	663.99	666.36	657.92	658.62	657.90
49	665.42	665.62	658.05	658.58	658.31
50	664.63	667.78	658.90	658.80	656.72
51	664.98	667.54	658.80	658.09	658.70
52	665.04	667.75	658.57	658.27	659.57
53	665.67	668.04	658.90	658.47	658.40
54	664.75	667.93	658.36	658.98	659.65
55	665.55	669.10	657.88	659.66	659.60
56	666.48	670.74	658.69	659.70	659.59
57	667.68	670.66	659.21	659.53	660.82
58	667.09	670.58	660.52	660.21	660.36
59	668.06	671.43	660.21	660.81	660.94
60	669.66	671.17	660.73	661.48	660.78
61	669.90	672.49	660.65	660.87	661.98
62	671.70	672.18	662.40	660.30	661.09
63	672.66	673.76	662.33	661.71	660.86
64		673.02	662.96	662.51	662.16
65		672.92	664.26	662.06	662.76
66		673.69	665.06	662.08	662.17
67		673.49	665.45	664.02	662.31
68		673.72	666.55	664.14	663.69
69		674.18	667.23	663.82	660.90
70		676.56	668.07	664.65	662.16
71		676.78	667.60	664.59	661.41

72			669.19	664.40	663.36
73			669.28	664.50	663.75
74			669.20	664.23	662.79
75			668.29	664.20	664.16
76			668.67	663.87	665.24
77			669.85	664.22	665.77
78			669.80	662.09	664.69
79			669.23	664.01	666.90
80			670.60	664.20	664.80
81			670.60	665.92	666.16
82			671.84	665.76	667.40
83			672.23	666.95	668.25
84				669.00	668.29
85				667.59	666.08
86				669.96	665.91
87				670.47	665.66
88				672.51	669.11
89				671.06	667.78
90					668.01
91					667.86
92					666.81
93					667.63
94					667.73
95					667.19
96					666.92
97					665.45
98					669.57

C.5 Processed thickness measurements of the nickel cantilever beams

Table C.7 Thickness measurements of the nickel cantilever beams.

Beam Length (μm)	Nickel Thickness (μm)		
	Loose die 3	Loose die 4	Loose die 5
1000	16.682	20.928	20.247
950	16.838	21.030	19.709
900	16.723	20.994	19.462
850	16.823	21.143	19.517
800	16.905	21.156	19.665
750	17.023	21.306	19.683
700	17.076	21.217	19.720

C.6 First mode resonant frequency measurements of the nickel cantilever beams

Table C.8 Resonant frequency measurements of the nickel cantilever beams.

Beam Length (μm)	Resonant frequency (Hz)		
	Loose die 3	Loose die 4	Loose die 5
1000	11420	14220	13710
950	12620	15680	14755
900	13820	17390	16235
850	15590	19400	18075
800	17640	21975	20350
750	20130	24935	23140
700	23210	28595	26500

C.7 Extracted Young's modulus results for the nickel film via numerical simulations

Table C.9 Extracted Young's modulus results for the nickel film via numerical simulations.

Beam Length (μm)	Young's modulus (GPa)		
	Loose die 3	Loose die 4	Loose die 5
1000	164	163	162
950	160	160	161
900	157	160	162
850	157	156	159
800	157	158	156
750	157	156	156
700	158	157	155

C.8 Deflection measurements for each fabricated micro bridge mechanism

Table C.10 Measurements for the free cantilever and substrate trench

Prototype	Loose die 1		Loose die 2	
	Vertical height of the free cantilever*	Depth of the substrate trench	Vertical height of the free cantilever*	Depth of the substrate trench
A1	81.658	22.639	76.594	22.667
A4	91.028	22.550	96.585	22.733
B1	47.503	22.679	42.852	22.687
B3	78.374	22.690	47.328	22.741
B4	82.993	22.712	48.381	22.786
C1	74.905	22.861	57.524	22.844
A2	78.101	22.610	85.409	22.569
A3	81.154	22.578	89.125	22.656
A5	82.317	22.590	86.012	22.688
B2	75.050	22.597	55.156	22.709
B5	75.739	22.768	47.594	22.724

*Measured from the tip of the free cantilever to the surface of the substrate trench.

C.9 Three layer thickness measurements for each fabricated micro bridge mechanism

Table C.11 Three layer thickness measurements near the anchor pads for each micro bridge mechanism on loose die 1.

Prototype	Bridge Mechanism thickness (μm)	
	Location 1	Location 2
A1	18.84	20.02
A4	21.90	21.28
B1	19.30	20.00
B3	20.76	21.47
B4	20.65	22.04
C1	19.96	21.65
A2	20.49	20.93
A3	21.43	21.33
A5	22.87	21.96
B2	20.13	20.72
B5	21.49	22.50

Table C.12 Three layer thickness measurements near the anchor pads for each micro bridge mechanism on loose die 2.

Prototype	Bridge Mechanism thickness (μm)	
	Location 1	Location 2
A1	20.74	19.32
A4	22.06	19.05
B1	19.40	19.42
B3	20.59	19.71
B4	20.10	20.57
C1	18.85	19.24
A2	20.57	19.27
A3	20.50	19.15
A5	21.09	19.26
B2	20.56	19.30
B5	20.46	20.43

Appendix D Maple Code

D.1 Maple Code to calculate the radius of the curvature based on a set of data points

The maple code developed in [100] was modified to suit the purpose of this thesis and is detailed in Table D.1.

Table D.1 The Maple code used to determine the radius of curvature [100].

Maple line code	Comments
> restart;	Clears the memory of any stored data
<pre>> DataCurve:= Matrix(1..2,1..21,{(1,1)=1.0029E-08,(1,2)=1.25901E-06,(1,3)=2.50802E-06,(1,4)=3.75701E-06,(1,5)=5.00601E-06,(1,6)=6.25501E-06,(1,7)=7.50401E-06,(1,8)=8.753E-06,(1,9)=1.0002E-05,(1,10)=1.1251E-05,(1,11)=1.25E-05,(1,12)=1.3749E-05,(1,13)=1.4998E-05,(1,14)=1.6247E-05,(1,15)=1.7496E-05,(1,16)=1.8745E-05,(1,17)=1.9994E-05,(1,18)=2.1243E-05,(1,19)=2.2492E-05,(1,20)=2.3741E-05,(1,21)=2.499E-05,(2,1)=1.00511E-05,(2,2)=1.00249E-05,(2,3)=1.00016E-05,(2,4)=9.9809E-06,(2,5)=0.000009963,(2,6)=9.9479E-06,(2,7)=9.9355E-06,(2,8)=9.9258E-06,(2,9)=0.000009919,(2,10)=9.9148E-06,(2,11)=9.9134E-06,(2,12)=9.9148E-06,(2,13)=0.000009919,(2,14)=9.9258E-06,(2,15)=9.9355E-06,(2,16)=9.9479E-06,(2,17)=0.000009963,(2,18)=9.9809E-06,(2,19)=1.00016E-05,(2,20)=1.00249E-05,(2,21)=1.00511E-05});</pre> $DataCurve := \begin{bmatrix} 2 \times 21 \text{ Matrix} \\ \text{Data Type: anything} \\ \text{Storage: rectangular} \\ \text{Order: Fortran_order} \end{bmatrix}$	<p>“DataCurve” is the variable used to store the Matrix of the data points used to fit a circle and calculate the radius or the radius of the curvature.</p> <p>The first row in the matrix is the x coordinates and the second row is the z coordinates.</p> <p>Note that the coordinates are in meters.</p>
<pre>> Kreis:= (x,z)->x^2+z^2-2*a*x-2*b*z-c=0; Kreis := (x, z) → x² + z² - 2 a x - 2 b z - c = 0</pre>	Sets the the general equation for a circle.
<pre>> Px:= convert(DataCurve[1],'list'); > Pz:= convert(DataCurve[2],'list');</pre> <p>(the output of this command is not shown due to its large size)</p>	Covert the first row of the matrix and store them in the variable “Px” and convert the second row the matrix and stores them into the variable “Pz”.
> gls:= {op(zip(Kreis, Px, Pz))};	Using the data, the corresponding system

(the output of this command is not shown due to its large size)	of equations is constructed.
> lsg:= linalg[leastsqrs](gls, {a,b,c}): (the output of this command is not shown due to its large size)	Using this equation to solve the over-determined system.
> r:= evalf(subs(lsg, sqrt(c + a^2 + b^2))); r := 0.0005667215391	The radius of the circle (or curvature) is then given by this equation. (Note that this result is in meters)
> r*1e6; #um 566.7215391	Thus, the radius (of curvature) in micrometers is given.

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