

MEMS Technology for Adaptive Sensors

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ABSTRACT

This research work presents the design, development and experimental validation of a bio-inspired microelectromechanical systems (MEMS) - based acoustic sensor with dynamically tunable resonance frequencies. The primary objective is to develop a sensor capable of efficiently analyzing, and processing information directly at the sensor level. Drawing inspiration from the human auditory system, the sensor mimics the ear's ability to respond selectively to different frequencies with high sensitivity. The dynamic frequency tuning capability allows the sensor to cover a broader frequency spectrum within a single sensor beam and minimizes the number of sensors required to cover acoustic ranges. The proposed MEMS sensor demonstrates two distinct approaches for dynamic frequency tuning:

i) Frequency tuning by geometric nonlinearity

ii) Frequency tuning by Ni-Ti shape memory alloys (SMAs)

In the first approach, a clamped-clamped micromechanical beam is employed to achieve up to 25% tunability in resonance frequency with low bias voltages (<1 V). This dynamic tuning capability enables frequency analysis of sound in hardware, extending the sensor's operational frequency range while maintaining high-quality factors. We show that for the fabricated sensors, DC actuation changes the beam's pre-deflection, this pre-deflection changes the resonance frequency of the sensor. A nonlinear dynamic model based on the Duffing oscillator equation describes the system behavior, including observed hardening and softening effects. Experimental results validate the sensor's ability to compensate for fabrication variabilities, such as thickness variation, and demonstrate its application in frequency component analysis of sound signals.

In the second approach, Ni-Ti SMA thin films are deposited on the backside of the MEMS sensor. These materials exhibit the shape memory effect (SME), enabling reversible frequency shifts through temperature-induced phase transformations. A frequency tuning of up to 25% is achieved in this work. Moreover, SME imparts a memory-like behavior to the sensor, with transformation hysteresis between transition temperatures further enhancing its functionality. This material-driven response marks a significant step toward the realization of an intelligent MEMS sensors (integrating

sensing, actuation, and a SMA) that can adapt by themselves without relying on external systems.

The integration of both tuning approaches enables frequency-selective sensing over a broader range within a single sensor. Potential applications include bio-acoustic monitoring, gas flow detection, and frequency-selective signal processing. These findings provide a foundation for advanced sensor networks and systems capable of real-time dynamic adaptation and memory-based frequency tuning.

ZUSAMMENFASSUNG

Diese Forschungsarbeit präsentiert das Design, die Entwicklung und die experimentelle Validierung eines bioinspirierten, Mikroelektromechanischen Systems (MEMS) – basierten Akustiksensors mit dynamisch abstimmbaren Resonanzfrequenzen. Das Hauptziel besteht darin, einen Sensor zu entwickeln, der in der Lage ist, Informationen effizient direkt auf Sensorebene zu analysieren und zu verarbeiten. In Anlehnung an das menschliche Gehör ahmt der Sensor die Fähigkeit des Ohrs nach, mit hoher Empfindlichkeit selektiv auf verschiedene Frequenzen zu reagieren. Die dynamische Frequenzabstimmbarkeit ermöglicht es dem Sensor, ein breiteres Frequenzspektrum innerhalb eines einzelnen Sensor abzudecken und minimiert die Anzahl der Sensoren, die zur Erfassung akustischer Bereiche erforderlich sind.

Der vorgeschlagene MEMS-Sensor demonstriert zwei unterschiedliche Ansätze zur dynamischen Frequenzabstimmung:

i) Frequenzabstimmung durch geometrische Nichtlinearität

ii) Frequenzabstimmung durch Ni-Ti-Formgedächtnislegierungen (SMAs)

Im ersten Ansatz wird ein beidseitig eingespanntes mikromechanisches Balkenelement verwendet, um eine Abstimmbarkeit der Resonanzfrequenz von bis zu 25 % bei niedrigen Spannungen (<1 V) zu erreichen. Diese dynamische Abstimmfähigkeit ermöglicht eine Frequenzanalyse von Schall im Hardwarebereich und erweitert den nutzbaren Frequenzbereich des Sensors bei gleichzeitig hoher Güte. Wir zeigen, dass bei den gefertigten Sensoren eine Gleichstromansteuerung die Vordeflektion des Balkens verändert, was wiederum die Resonanzfrequenz des Sensors beeinflusst. Ein nichtlineares dynamisches Modell basierend auf der Duffing-Oszillator-Gleichung beschreibt das Systemverhalten, einschließlich der beobachteten Härtungs- und Weichungseffekte. Experimentelle Ergebnisse bestätigen die Fähigkeit des Sensors, Fertigungsschwankungen, wie z. B. Dickenvariationen, zu kompensieren, und demonstrieren seine Anwendung bei der Frequenzkomponentenanalyse von Schallsignalen.

Im zweiten Ansatz werden Ni-Ti-SMA-Dünnschichten auf der Rückseite des MEMS-Sensors abgeschieden. Diese Materialien zeigen den Formgedächtniseffekt (SME),

der reversible Frequenzverschiebungen durch temperaturinduzierte Phasenumwandlungen ermöglicht. In dieser Arbeit wird eine Frequenzabstimmung von bis zu 25 % erreicht. Darüber hinaus verleiht der SME dem Sensor ein gedächtnisartiges Verhalten, wobei die Transformationshysterese zwischen den Übergangstemperaturen seine Funktionalität zusätzlich verbessert. Diese materialgetriebene Reaktion stellt einen bedeutenden Schritt in Richtung der Realisierung intelligenter MEMS-Sensoren dar (Integration von Sensorik, Aktuatorik und SMA), die sich eigenständig anpassen können, ohne auf externe Systeme angewiesen zu sein.

Die Integration beider Abstimmungsansätze ermöglicht eine frequenzselektive Erfassung über einen breiteren Bereich innerhalb eines einzelnen Sensors. Potenzielle Anwendungen umfassen bioakustisches Monitoring, Gasstromdetektion und frequenzselektive Signalverarbeitung. Diese Ergebnisse bilden die Grundlage für fortschrittliche Sensornetzwerke und -systeme, die in der Lage sind, sich in Echtzeit dynamisch anzupassen und speicherbasierte Frequenzabstimmung zu realisieren.

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LIST OF SYMBOLS AND ABBREVIATIONS

MEMS – Microelectromechanical systems

SNR – Signal to noise ratio

F – Force

v – Velocity

V – Voltage

I – Current

x – Displacement

q – Charge

M – Mass

L – Inductance

R – Resistance

nN – Nanonewton

FEM – Finite element modelling

μm – Micrometer

mm – Millimeter

nm – Nanometer

DC – Direct current

KOH – Potassium hydroxide

PVD – Physical vapor deposition

CVD – Chemical vapour deposition

PLD – Pulsed laser deposition

ALD – Atomic layer deposition

IHCs – Inner hair cells

OHCs – Outer hair cells

C-C beam – Clamped-clamped micromechanical beam

σ – Stress

ϵ – Strain

ϵ_x – Axial strain

ϵ_a – Axial strain of original neutral axis

ϵ_T – Total axial strain

W – Total strain energy

U – Potential energy

E – Modulus of elasticity

x – Displacement

$w(x)$ – Transverse displacement at x

$u(x, y)$ – Axial displacement at x, y

M – Bending moment

I – Moment of inertia

$Q(x)$ – Shear force

$q(x)$ – Transverse load

m – Effective mass

C – Damping coefficient

ζ – Damping ratio

k_{1sp} – Linear spring constant of the sensing part of beam

k_{1tp} – Linear spring constant of the tuning part of beam

k_{3tp} – Nonlinear Spring constant of tuning part of beam

z – Beam displacement

A_0 – Amplitude

ω – Driving frequency

θ – Temperature difference of the beam with the surrounding/mounting

U – Applied voltage

C_1 – Transfer factor from temperature to deflection

C_2 – Transfer factor from voltage to temperature

P_{heater} – Resulting heating power
 R – Resistance of the heater
 U_{dc} – DC voltage
 U_{ac} – AC voltage
 τ – Time constant for temperature variations
 z_0 – Static deflection (working point)
 α – Linear system parameter
 β – Quadratic system parameter
 γ – Cubic nonlinear system parameter
 K_f – Correction factor
 dx – Original length of the beam
 ds – Deformed length
 f – Natural resonance frequency of the sensor
 δ_n – Pre-factor for the n^{th} mode
 ρ – Density of silicon
Al – Aluminium
Si – Silicon
 l_{sp} – Length of the sensing beam
 w_{0sp} – Width at the beam base of sensing beam
 w_{1sp} – Width at the beam top of sensing beam
 t_{sp} – Beam thickness in bending direction of sensing beam
 l_{1tp} – Length of the tuning beam
 l_{2tp} – Length of middle part of the tuning beam
 w_{tp} – Width of the tuning beam
 t_{tp} – Beam thickness in bending direction of tuning beam
sp – Prefix for the sensing beam
tp – Prefix for the tuning beam

Q – Quality factor

Π_l – Longitudinal piezoresistive coefficients

Π_t – Transverse piezoresistive coefficients

ρ – resistivity of doped silicon

L – Length of the resistor

A – Cross-sectional area of the resistor

2D – Two-dimensional

3D – Three-dimensional

K – Kelvin

Hz – Hertz

kHz – Kilohertz

SiO₂ – Silicon dioxide

PECVD – Plasma enhanced chemical vapor deposition

BOE – Buffered oxide etching

SF₆ – Sulphur hexafluoride

PCB – Printed circuit board

LDV – Laser Doppler Vibrometer

LSM – Laser scanning microscopy

cN – Centi Newton

ms – Milliseconds

°C – Degree Celsius

mW – Milliwatt

C_f – Linear actuation efficiency coefficient

η_{fluid} – Dynamic viscosity

ρ_{fluid} – Density of the fluid

μPa – Micro pascal

Ω – Ohm

Au-Cd – Gold-cadmium

Cu-Zn – Copper- zinc

NiTi – Nickel Titanium

Atomic % – Atomic percent

SMA – Shape memory alloys

SME – Shape memory effect

SE – Superelasticity

N₂ – Nitrogen inert gas

OWSME – One-way shape memory effect

TWSME – Two-way shape memory effect

M_f – Martensitic finish

M_s – Martensitic start

A_s – Austenitic start

A_f – Austenitic finish

ζ₀ – Onset of current phase transformation

$\alpha_{MA}(T)$ – Fraction of Ni-Ti alloy crystals in martensitic to austenitic phase

$\alpha_{AM}(T)$ – Fraction of Ni-Ti alloy crystals in austenitic to martensitic phase

f_{MA} – Frequency transitioning from martensitic to austenitic phase

f_{AM} – Frequency transitioning from austenitic to martensitic phase

f_{MAS} – Frequencies at start transformation temperatures for martensite phase to austenite phase

f_{MAF} – Frequencies at finish transformation temperatures for martensite phase to austenite phase

f_{AMS} – Frequencies at start transformation temperatures for austenite phase to martensite phase

f_{AMF} – Frequencies at finish transformation temperatures for austenite phase to martensite phase

T_{MA} – Transformation temperatures for martensite to austenite phase

T_{AM} – Transformation temperatures for austenite to martensite phase

T_{SMA} – Start transformation temperatures for martensite to austenite phases

T_{FMA} – Finish transformation temperatures for martensite to austenite phases

T_{SAM} – Start transformation temperatures for austenite to martensite phases

T_{FAM} – Finish transformation temperatures for austenite to martensite phases

β – Steepness of logistic curve

mTorr – Millitorr

sccm – Standard cubic centimeters per minute

SEM – Scanning electron microscopy

EDX – Energy-dispersive X-ray spectroscopy

SEM-EDX – Scanning electron microscopy- energy dispersive X-ray spectroscopy

SE – Superelasticity

kV – Kilovolt

R_T – Resistance of RTD at a given temperature

R_0 – Resistance of RTD at reference temperature

α_0 – Temperature coefficient of resistance

PID controller – Proportional Integral Derivative controller

RTD – Resistance temperature detector

CHAPTER 1

INTRODUCTION AND MOTIVATION

1.1 Thesis content and objectives

Electronic speech processing systems often struggle in realistic auditory environments with low signal to noise ratios (SNR), unlike biological hearing systems which perform remarkably well under such conditions. A key distinction between the two lies in the features incorporated at the sensing stage. Typically, sound processing systems are composed of three core components: the sensing unit, the pre-processing unit, and the processing unit. In recent years, the improvements in the performance of sound processing systems have largely attributed to advancements in the pre-processing and processing units ¹. Microelectromechanical systems (MEMS) microphones have widely adopted in modern auditory sensing applications due to their compact size, low power consumption, and compatibility with large-scale bulk fabrication processes. As a result, they are widely integrated into the devices such as smartphones, hearing aids, smart speakers, and Internet of Things (IoT) devices ²⁻⁴. However, conventional MEMS microphones, including those manufactured by Knowles, Infineon, and TDK still face limitations in dynamic range and SNR performance. For example, Infineon's IM69D130 microphone ⁵ offers 69 dB(A) SNR and a dynamic range of 105 dB, which, while adequate for many applications, may be insufficient in environments with fluctuating or extreme acoustic conditions. Likewise, TDK's C928 MEMS microphone⁶ offers a 66 dB(A) SNR and maintains low distortion at high sound pressure levels.

These conventional MEMS microphones are effective for many consumer applications, they still face several limitations. These include omnidirectional sensitivity, which requires additional hardware like microphone arrays for spatial filtering, as well as a lack of frequency selectivity and adaptive gain control, limiting their ability to adapt in real time to changing auditory environments ⁷⁻⁹. These limitations highlight the need for a new generation of sensing technologies that go beyond present design paradigms ^{10,11}. To address these shortcomings, this research takes inspiration from the human auditory system. Bio-inspired acoustic sensing is an emerging field that draws design ideas from biological hearing systems, especially the human ear. The state of art involves drawing inspiration from auditory mechanisms

such as the cochlea and the hair cells on the basilar membrane, which perform the signal conditioning and feature extraction at sensing/transduction stage itself. Modern approaches aim to mimic key features of biological hearing, including frequency selectivity, directional sensitivity, and a wide dynamic range.

Technological advances in bio-inspired MEMS sensors have recently attracted attention in the field of acoustic sensing ^{12,13}. A more advanced bio-inspired emulation has already been achieved with MEMS “cochlea” systems. Guerreiro et al., demonstrated a MEMS microphone that can be designed to pursue the concept of frequency-agile and adaptive tuning ¹⁴. Haronian and MacDonald mimic the behaviour of basilar membrane by mechanically filter the acoustic inputs into frequency ranges¹⁵. The acoustic MEMS sensor of White and Grosh integrated mechanical structures with the piezoresistive transduction elements ¹⁶. Tao Xu et al., developed a polymeric cantilever-based sensor array that mimics the mammalian cochlea for use in hearing prostheses ¹⁷, while Tanaka et al., proposed the novel mechanical model of a cochlea known as fishbone structure and fabricated it using silicon micromachining ¹⁸. Furthermore, Jung et al., developed a flexible piezoelectric acoustic sensor that detect a wide range of sound signals with excellent sensitivity ¹⁹, whereas Jang et al., fabricated a novel MEMS piezoelectric cantilever array that showed the frequency selectivity in acoustic range ²⁰. Although the frequency range does not include those in the typical acoustic range, they have effectively demonstrated its potential for application in frequency selectivity. For biomimetic multitunable frequency band control, Wang et al., reported a highly sensitive and miniaturized piezoelectric mobile acoustic sensor ²¹. Meanwhile, Harada et al., described the cantilever-based micromechanical acoustic sensor that employed piezoresistors to detect the mechanical vibrations of cantilever and further realizes frequency selectivity ²². The aforementioned review identified the challenges in developing a MEMS cochlea, such as fabrication variabilities, technological constraints, and determine cochlea-like features in the experimental realization. Therefore, it is necessary to emulate a biological approach.

The objective of this research is to develop a bio-inspired acoustic MEMS sensor capable of efficiently analyzing, and processing the information directly at the sensor level (see *Figure 1.1*). The key goal is to develop a bio-inspired acoustic MEMS sensor, whose resonance frequency can be dynamically tuned over a large range by

applying a small DC bias voltage (less than 1V). This frequency tuning approach is highly significant, as it enables a single sensor beam to cover a broad range of frequencies ranging from 20 Hz to 20 kHz, thereby reducing the number of sensors needed to cover full acoustic spectrum.

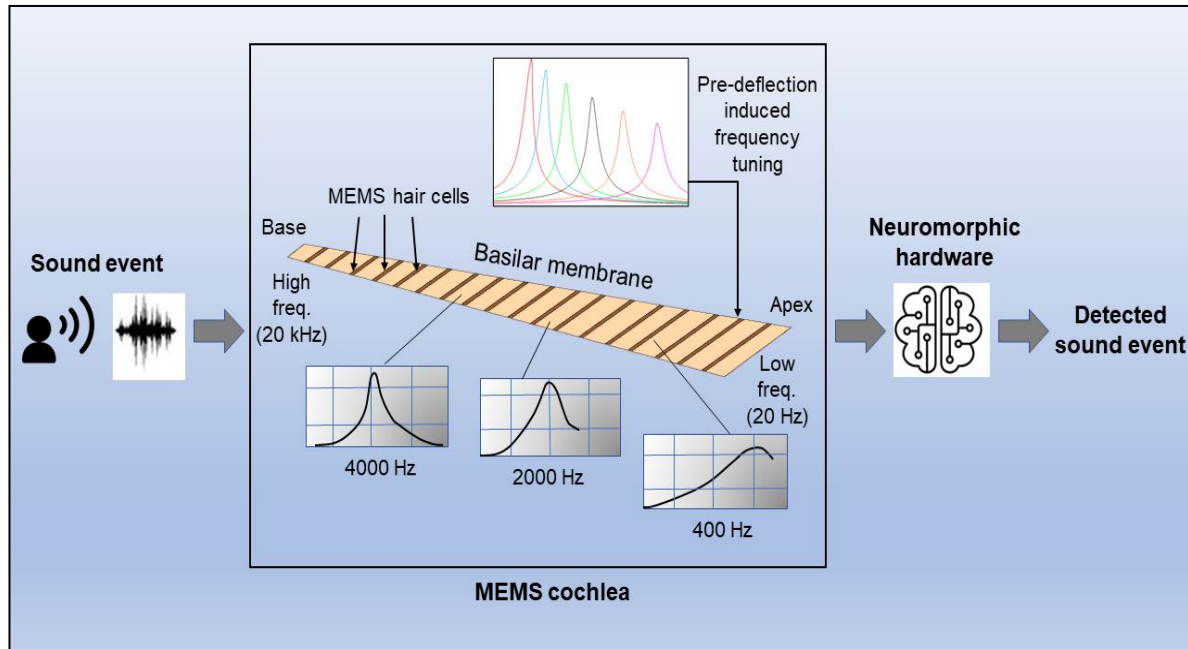


Figure 1.1 Bio-inspired sound processing system.

The proposed MEMS-based acoustic sensor presents several advancements over the conventional ones:

- i) We present a MEMS sensor with a tunable resonance frequency that can be shifted by up to 1.2 kHz.
- ii) The sensor exhibits filter-like features that can be easily modified using a low DC bias voltage ($<1V$).
- iii) Using such a low voltage for tuning enables fast, dynamic control of the resonance frequency, making the sensor suitable for real-time acoustic sensing applications ^{23,24}.
- iv) Geometric nonlinearity, notably the use of a clamped-clamped micromechanical beam (C-C beam), allows the tuning of resonant frequency by static deflection.

In this dissertation, a frequency tunability approach is thoroughly investigated utilizing two different methodologies: i) frequency tuning of MEMS sensor using geometric nonlinearity, and ii) frequency tuning of MEMS sensor functionalized by Ni-Ti shape

memory alloys (SMAs). The proposed MEMS sensor is fabricated at ZMN (Central facility for micro- and nanotechnologies), Technische Universität Ilmenau, Germany. The developed sensor is inspired by the functionality of the cochlea and can be used in a variety of systems (e.g., hearing aids, human-machine interaction, smartphones etc).

1.2 Human hearing

Human hearing is capable of detecting a wide range of sound frequencies with high precision. This is largely due to the cochlea, where hair cells along the basilar membrane respond to specific frequencies and perform early-stage signal processing. This natural mechanism inspires the design of the bio-inspired MEMS acoustic sensor developed in this research, which aims to replicate the frequency selectivity and signal analysis capabilities of the human ear directly at the sensor level. In the human ear, hearing is the process by which mechanical energy in the form of sound vibrations is converted to the electrical signals ²⁵. This is facilitated by the complex structure of the ear, which comprises of the outer, middle, and inner ear. Outer ear, which includes the pinna and external auditory canal, collects sound waves and propagates them to the ear drum. The middle ear, consists of the ossicles (malleus, incus, and stapes), amplifies and transmits vibrations from the eardrum to the cochlea. The cochlea is a fluid-filled, spiral shaped cavity ²⁶. In the auditory system, hair cells are specialized sensory cells located within the cochlea of the inner ear. These thousands of tiny hair cells convert mechanical vibrations into electrical signals, which are then transmitted to the brain via the auditory nerve for interpretation ²⁷. There are two primary types of hair cells: Inner hair cells (IHCs), responsible for transmitting sound information to the brain, and Outer hair cells (OHCs), which amplifies the sound and improve frequency selectivity ²⁸. The cochlea consists of the organs of Corti that are surrounded by a fluids of the scala vestibuli and scala tympani. The organ of Corti is situated on the basilar membrane, which is responsible for producing the vibrations (see *Figure 1.2 (a)*). In addition to sensing, the cochlea also performs frequency decomposition of the sound input. The basilar membrane in cochlea is responsible for a frequency selectivity ^{29,30}. It has low mass and high stiffness near the oval window or at the start of the cochlea, making it sensitive to higher frequencies in this area. Acoustic waves of specific frequency cause the basilar membrane to vibrate with a considerable

amplitude at its resonance frequency at a designated location on the membrane (see Figure 1.2 (b)).

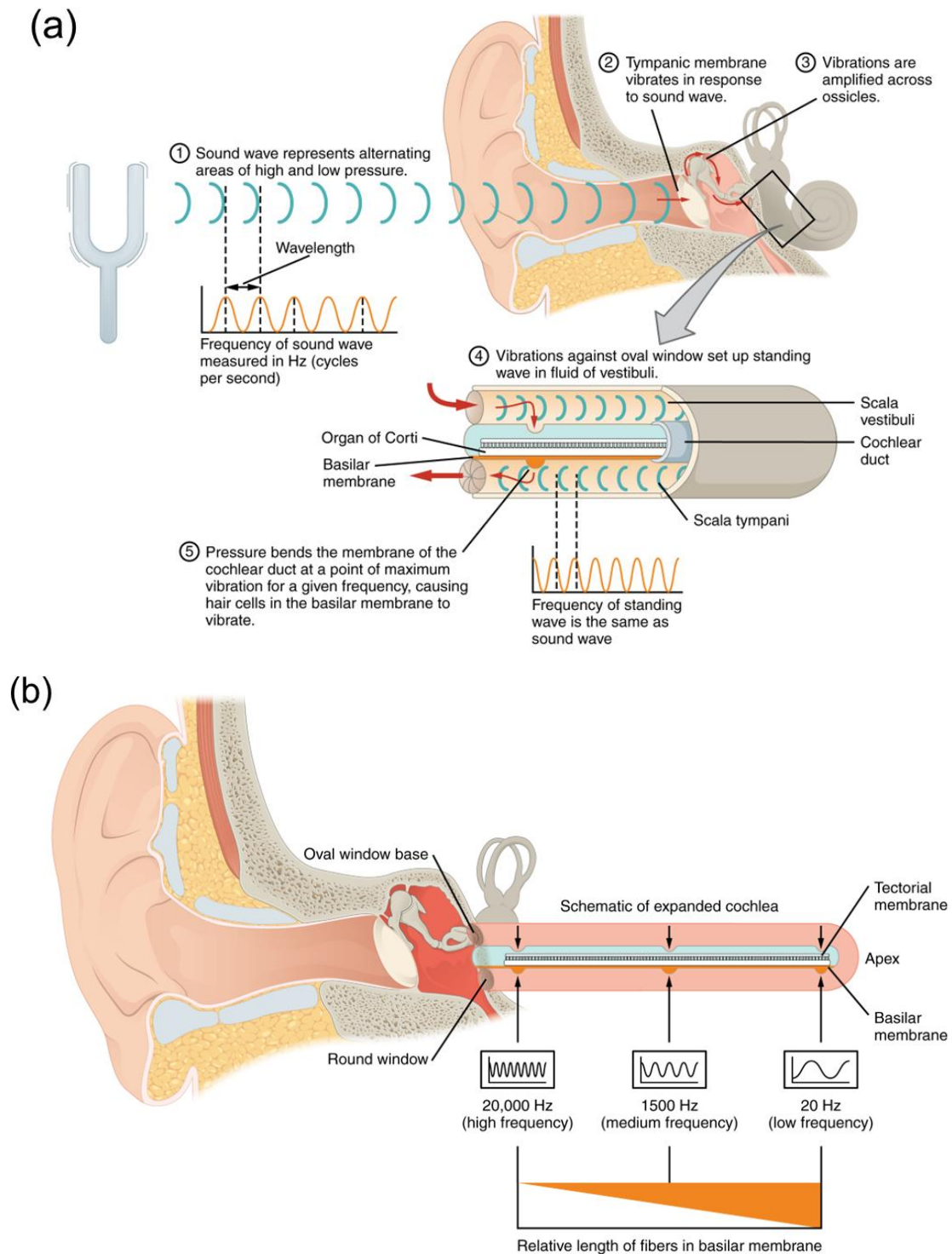


Figure 1.2 (a) illustrates the process of movement of sound waves through the ear, with each stage providing a detailed account of the process, and (b) shows how various sound frequencies are coded in the cochlea (adapted from ²⁵).

The hair cells at this location are stimulated by this resonance, leading to the realization of frequency selectivity. As we approach towards the apex of basilar membrane, the mass increases and the stiffness decreases, making it responsive to lower frequencies in this region. Biological auditory systems rely on compact and highly sensitive structures. MEMS technology facilitates the development of micro-scale acoustic sensors that emulate these biological systems in both size and sensitivity. MEMS sensors provide high sensitivity at low power consumption, making them ideal for bio-inspired acoustic sensing^{10,31}. Consequently, the following sections provide an introduction and technology for MEMS.

1.3 Introduction to MEMS

MEMS are one of the important fields of research and are extensively employed in the development of novel technologies, featuring a diverse array of innovative applications¹². MEMS is a revolutionary process technology that has gained popularity in bio-inspired sensors due to its smaller size, low damping capabilities, good thermal response, sensitivity to the environment, fast heating and cooling due to low thermal mass, exhibiting nonlinear behavior, and easy integration of electronic functionality such as filtering and amplification^{32–34}. MEMS sensor devices can enhance the systems functionality. Moreover, MEMS are unified package that combines mechanical components (vibrating structures, membranes, springs) with electronic components. There are a wide range of MEMS sensors and devices available in the market. Among these, MEMS resonators are microscale mechanical structures capable of vibrating at their natural frequency when stimulated by an external excitation. In this process, the sensor is stimulated to vibrate by translating/converting an electrical signal into a force and then applying it to the device. Vibrations in micromechanical structures are subsequently detected and transformed back into electrical signals using a variety of transduction techniques, including capacitive, piezoelectric, piezoresistive, and so on. Furthermore, to represent mechanical characteristics with electrical domain, it is necessary to establish an appropriate correspondence between mechanical and electrical values, as outlined in *Table 1.1*³⁵.

Sr. No	Mechanical domain	Electrical domain
1	Force F	Voltage V
2	Velocity v	Current I
3	Displacement x	Charge q
4	Mass M	Inductance L
5	Damping ζ	Resistance R

Table 1.1 Correspondence between mechanical and electrical values.

One of the example of such microsensor is the cantilever - based MEMS sensors. These sensors have the potential to be of great significance due to their inherent advantages, such as their high sensitivity, ease of integration with electronics, and mass/batch production capability. Additionally, heating and cooling of these sensors can be carried out in microseconds. For cantilever - based sensors, a wide number of readout techniques and actuation mechanisms have been developed. Common methods include electrostatic actuation^{36–39}, which offers high frequency response and low power consumption but requires a high driving voltage; piezoelectric actuation^{40–43} which provides high sensitivity, low driving force and displacement per unit voltage⁴⁴; piezoresistive, magnetostrictive, thermal, and so on⁴⁵. In the present work, the main operating principle of the sensor is based on bimorph thermomechanical actuation. The sensor uses integrated electrothermal micro-heaters to induce localized heating and controlled thermal expansion in a bimorph structure. The thermal actuator combined with design allows the sensor to adapt to different frequencies without requiring high-voltage input⁴⁶. While piezoresistive elements are used for readout, the primary functional mechanism is thermal-mechanical. This aspect will be discussed in detail in the following chapters.

Due to the digital revolution, and modern electronics, way of information processing is rapidly approaching its limits and consuming an enormous quantity of energy. The energy requirements of modern computational architectures are tremendous. The solutions accompanying with Industry 4.0, smartphone applications are dependent on energy-efficient hardware. To reduce the energy consumption, and further develop energy efficient systems and devices, one approach would be to take inspiration from

biology and mimic its functionality. A variety of natural sensory systems have been developed and operate in distinctive ways that attract attention, demonstrate impressive performance and provide as a rich source of inspiration for the development of artificial sensory systems (see *Figure 1.3*). MEMS technology has the potential to achieve this objective.

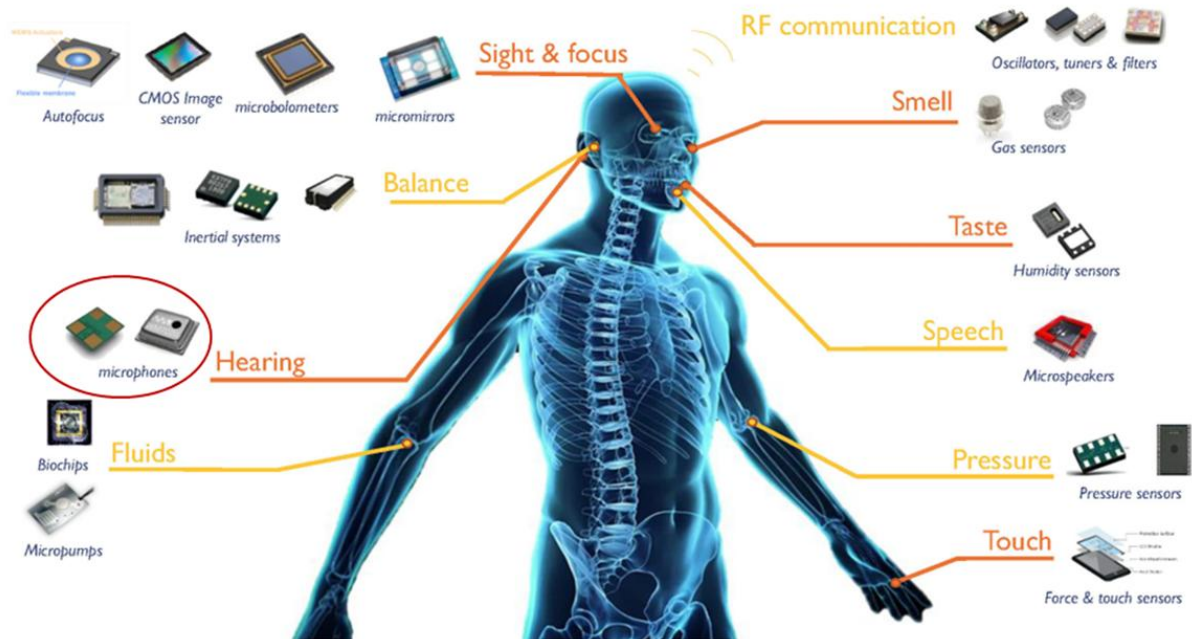


Figure 1.3 Mimicking human senses for different applications with MEMS technology (adapted from ⁴⁷).

MEMS companies are interested in developing energy efficient devices that mimics the functionalities of our human senses. These devices have the potential to serve as a real interface between the humans and the environment. Over the years, MEMS have played a crucial role in advancing miniaturized sensors and actuators. This technology has become a prominent player in a variety of applications due to its simplicity of integration with electronics, interface with the environment and so on. In recent decades, the demand for these devices has grown rapidly, particularly for accelerometers, gyroscopes, microphones, pressure sensors, and IoT based sensors⁴⁸. They are now essential in a variety of industries, including automotive, electronics, defense, aerospace, smart watch applications, smart phones, wearable and consumer electronics, biomedical systems, and smart devices ^{49,50}.

1.4 Technology for MEMS

Recent technological progress has made it possible to fabricate extremely small and precise sensors, though the manufacturing process remains highly complex and requires exceptional precision-especially when developing bio-inspired sensor designs ⁵¹. The main processes involved in producing such sensors include:

1. Thin film deposition
2. Patterning (photolithography)
3. Etching (wet and dry)

1.4.1 Thin film deposition

Thin film deposition is a process used to deposit a thin layer of material on the surface of the wafer. Two common methods are used to deposit these materials onto the substrate: i) Vapour deposition (Physical vapor deposition (PVD), and Chemical vapour deposition (CVD)), and ii) Electroplating. Physical and chemical vapour deposition: Physical vapour deposition is a physical process that does not involve any chemical reactions during the deposition process. PVD involves vaporizing a material from a solid or liquid source in a vacuum or low-pressure environment and then depositing it onto a substrate ⁵². PVD methods are categorized as: i) evaporation, ii) sputtering, iii) pulsed laser deposition (PLD), and iv) arc vapour deposition. In contrast, chemical vapour deposition involves the chemical reaction of gaseous precursors with the substrate surface to produce a solid thin film. This technique can provide high-purity and high-performance coatings ⁵³. The CVD methods are classified as: i) thermal CVD, ii) plasma-enhanced CVD, iii) low pressure CVD, iv) atmospheric pressure CVD, and v) atomic layer deposition (ALD) ⁵⁴. Amongst all, the PVD technique has been used in our study, as discussed in chapter 4.

1.4.2 Photolithography

Photolithography is a process used to transfer patterns from a photomask onto a silicon wafer using light. Photolithography is essential for creating high-resolution features, which are critical to the performance and reliability of MEMS devices ⁵¹. It is a key step in fabricating the bio-inspired MEMS acoustic sensor developed in this work. The process starts by coating the wafer with a light-sensitive substance known as photoresist. A photomask with the desired pattern is aligned over the wafer, and

ultraviolet (UV) light is used to expose the specific areas of the photoresist. Depending on whether a positive or negative photoresist is used, either the exposed or unexposed areas are developed and washed away. This patterned photoresist layer acts as a mask for the subsequent steps such as etching or material deposition. This patterning allows precise shaping of microstructures like the sensor beam and electrodes.

1.4.3 Etching

Etching is a fundamental process in MEMS fabrication used to selectively remove the material from a substrate to create desired microstructures, following with the pattern defined by photolithography. This work employs wet and dry etching processes, depending on the material type, required precision, and etch depth.

i) Wet etching: Wet etching involves the use of liquid chemicals to react with and dissolve exposed materials. The wafer is typically immersed or sprayed with an etchant, which selectively removes the exposed regions while leaving masked areas unaffected. Wet etching is a simple and cost-effective process. However, it offers limited control over etch profiles and may result in undercutting.

ii) Dry etching: Dry etching uses plasma or ion-assisted techniques to remove the material with high precision and excellent control over etch profiles. The wafer is placed in a reaction chamber, and gases are stimulated using RF energy to form the ions and radicals. These species interact with the wafer surface, allowing anisotropic etching with well-defined vertical sidewalls. Dry etching is particularly useful for applications that require high resolution and complex micro-patterning. When appropriately selected and applied, these etching processes allow for the precise formation of MEMS components, which are essential for sensor functionality in this work. *Figure 1.4* presents the different techniques used for MEMS sensor fabrication. A detailed overview of the fabrication steps, together with a schematic representation of the fabricated sensor, is provided in *Figure 4.2(a)*.

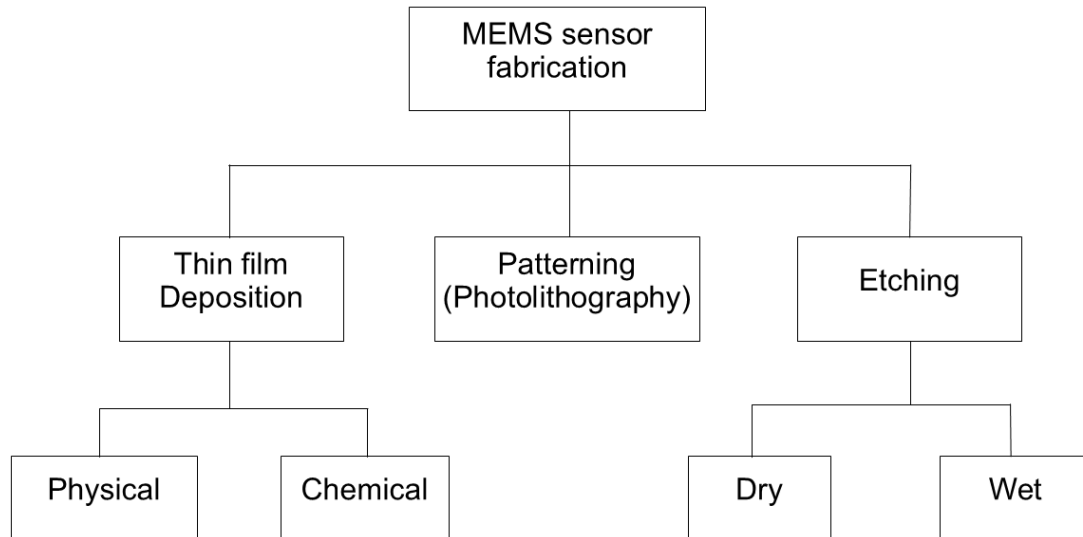


Figure 1.4 Different methods employed for the fabrication of MEMS sensors, including thin film deposition (physical and chemical methods), patterning (photolithography), and etching (dry and wet processes).

1.5 Organization of dissertation

The dissertation is organized into the following six chapters:

Chapter 1 presents an overview of the introduction and motivation behind this research. The chapter begins with the thesis contents and main objectives of this research work. In addition, the significance of a bio-inspired sound processing system in relation to the primary objective of this research is discussed. Since the developed sensor is inspired by the functionality of the human hearing, an overview of human hearing is also provided. This chapter further introduces technology for MEMS and its relevance to the development of the sensor.

Chapter 2 focuses on the design considerations for a bio-inspired acoustic MEMS sensor. The chapter begins with a discussion of the state of art of the cantilever concept, followed by a design for the proposed sensor. The design aspects of the MEMS sensor is comprehensively covered, including a geometrical parameter analysis of both the sensing and tuning parts. The dynamic behavior of micromechanical beams is described in detail, beginning with Euler-Bernoulli theory, followed by the non-linear oscillator: Duffing, and its dynamics on the sensor system. The phenomena of spring hardening and softening, as well as the governing equations and system nonlinearities, are presented and thoroughly analyzed.

Chapter 3 presents the finite element modelling approach and assumptions used in the development of the MEMS sensor. The dynamic modelling approach and the testing of geometric nonlinearity are discussed. This chapter details the various modules and studies employed in the COMSOL Multiphysics simulation analysis, including solid mechanics, electric current, heat transfer in solids interface, followed by a stationary study and an eigen frequency study. Furthermore, the validation of nonlinearity assessment have been investigated, and displacement curves are obtained under various loading conditions. Finally, frequency tuning analysis under DC excitation are performed using COMSOL simulation, and the response amplitude as a function of driving frequency for various DC voltages are computed.

Chapter 4 presents a detailed description of the development of a frequency tunable bio-inspired acoustic MEMS sensor using geometric nonlinearity. The need of frequency tunability is initially discussed in this chapter. The fabrication of sensor is then presented. The measurement results for electrical and acoustic actuation, as well as the dependence of resonance frequency on applied voltage, have been thoroughly investigated. A comparison of acoustic measurement and simulation results is also presented. Moreover, the application of frequency tuning for frequency analysis of sound input have been investigated.

Chapter 5 presents the development of an intelligent MEMS sensor with tunable frequency, which is functionalized with Ni-Ti shape memory alloy. The chapter begins with an introduction and motivation for using SMAs in MEMS sensors, emphasizing their unique thermo-mechanical properties and potential for intelligent sensing applications. The shape memory effect and its associated phase transformation behavior are discussed in detail. The modelling of Ni-Ti SMAs is then discussed. The fabrication of sensors, including deposition cycles, associated challenges, and characterization of Ni-Ti thin films, is thoroughly investigated. The results and discussion section presents frequency tuning outcomes for sensors with austenitic and martensitic phase transformations. Additionally, the pulse measurement results of shape memory alloys are examined.

Chapter 6 presents the summary and future development work of bio-inspired acoustic MEMS sensor, including the redesign of actuator.

CHAPTER 2

DESIGN CONSIDERATIONS IN BIO-INSPIRED ACOUSTIC MEMS SENSOR

2.1 State of art of the cantilever concept

Cantilevers are microscale beam-like structures that are widely used in MEMS due to their high sensitivity, compact design, and versatility in sensing and actuation applications. Recent advances in MEMS technology have enabled the development of cantilever-based sensors with improved sensitivity, frequency selectivity, and integration capabilities. Among these developments, biomimetic sensor designs particularly inspired by the mammalian cochlea, have received a lot of attention for their ability for frequency selectivity. The present work builds on this approach by designing a MEMS-based, cochlea-inspired sensor, which is presented in the following sections.

2.1.1 Sensor design

In this work, a sensor inspired by mammalian cochlea and realized using MEMS technology is presented²³. As can be seen in *Figure 2.1*, the sensing element consists of piezoresistors configured in a Wheatstone bridge arrangement. A micromechanical sensor utilizing piezoresistors in a Wheatstone bridge configuration detects the beam motion, while electrothermal aluminium micro-heaters facilitate bimorph pre-deflection and actuation. Our device consisted of two main parts that worked together. To incorporate a nonlinear stiffness into our design, the realized sensor comprises two parts: (i) the sensing part, and (ii) the tuning part as illustrated in *Figure 2.1*. The sensing part comprises a larger beam utilized for sensing, i.e., sound detection. The geometric dimensions have been selected to attain a high sensitivity for sound excitation¹. One end of the beam is fixed to the chip base, while the other end connects to the tuning part of the beam. The tuning part is a smaller, C-C beam, incorporated to enable the tuning of resonance frequency of the sensing part. This is due to the hardening phenomenon that rapidly manifests when the beam is driven further out of the plan. A schematic representation of the clamped-clamped

micromechanical beam, along with a detailed theoretical derivation, is presented in Section 2.3.3 (*Figure 2.8*).

Every microcantilever possesses a distinct natural resonance frequency. The natural frequency is dependent on the geometrical parameters such as spring stiffness, and mass. Adding mass to the beam alters its natural frequency, depending on the amount of mass added. The spring constant is a crucial parameter to consider while designing the sensor, as it significantly affects the resonance frequency of the sensor. To determine the spring constants and the corresponding deflection, the geometrical dimensions of sensing and tuning part must be considered. The spring constant depends on the length (l), width (w), thickness (t), and the modulus of elasticity (E) of the sensing or tuning part, as well as on the clamping condition. The length and width for all three sensors can be measured from the fabricated sensor directly using microscope images. The thickness cannot be measured directly. In the design and analysis of microelectromechanical systems (MEMS), the thickness of clamped-clamped (C-C) beams is an important parameter that directly influences deflection behavior under applied loads. It is an essential factor for determining whether the beam experiences small or large deflections. This is particularly important for numerous reasons: i) beam thickness determines bending stiffness and hence the mechanical response of MEMS structures ⁵⁵, and ii) MEMS sensors often function in conditions where geometric nonlinearities are significant, accurately assessing when a beam transitions from linear to nonlinear deflection ⁵⁶. The linear spring constant k_{1sp} of the sensing part can be approximated by a trapezoidal beam with a base width w_{0sp} and top width w_{1sp} , expressed as ⁵⁷:

$$k_{1sp} = \frac{E w_{0sp} t_{sp}^3}{4 l_{sp}^3} \frac{1}{K_f} \quad (2.1)$$

Here, K_f is the correction factor which depends on the ratio $r = w_{1sp}/w_{0sp}$ and can be written as:

$$K_f = \frac{3r}{(r-1)^3} \left[(1-r) - \frac{(1-r)^2}{2r} + r \ln r \right] \quad (2.2)$$

Due to the realized size and clamping circumstances, the sensing part exhibits a linear stiffness (k_{1sp}), whereas the stiffness of the tuning part comprises both, a linear part (k_{1tp}), and a nonlinear part (k_{3tp}), respectively. The indexes sp and tp represent the

prefixes for sensing and tuning parts, respectively. The sensing part alone would provide a linear response to small vibration amplitudes. The static deflection is thereby set by applying a static voltage at the actuator, thereby defining the working point of the entire sensor system, which can be utilized to modify its resonance frequency. The tuning bridge part alone will provide the equivalent tuning performance; but it will exhibit limited sensitivity to acoustic input signals owing to its geometrical dimensions and clamping. The sensitivity is primarily influenced by the area of the device, clamping conditions and sound path.

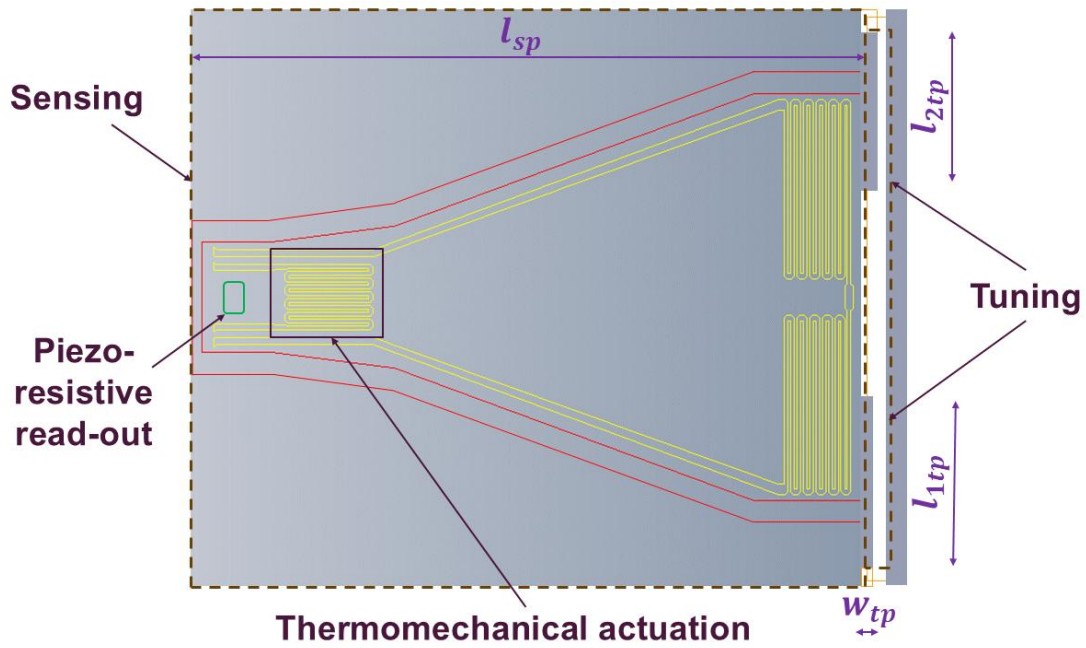


Figure 2.1 2D drawing of a bio-inspired MEMS sensor, which includes sensing part, and a clamped-clamped beam (tuning part).

Electrothermal aluminium-based microheaters on the top of silicon beam are employed to provide deflection and actuation via the bimorph effect^{58,59}. The beam is heated by applying a voltage (constant voltage (DC) and alternating voltage (AC)) to the aluminium loop, resulting in resistive heating that induces a temperature change. The differences in coefficient of thermal expansions between aluminium (Al) and silicon (Si) leads to a distinct thermal strain, resulting in beam deflection.

The displacement $z(t)$ is splitted into static and two harmonic parts. The static part provides the device response as static deflection z_0 , which depends on $U_{dc}^2 + \frac{U_{ac}^2}{2}$. The harmonic part at the driving frequency depends on $2U_{dc}U_{ac}$ and at twice driving frequency it is depending on $\frac{U_{ac}^2}{2}$. The resulting heating power is expressed as:

$$P_{heater} = \frac{1}{R} \left(U_{dc}^2 + \frac{U_{ac}^2}{2} + 2U_{dc}U_{ac} \cos \omega t + \frac{U_{ac}^2}{2} \cos 2\omega t \right) \quad (2.3)$$

Here, R denotes the resistance of heater, U_{dc} represents the DC voltage, U_{ac} signifies the AC voltage, and ω indicates the driving frequency.

2.1.2 Piezoresistive readout

In the fabrication of MEMS sensors, piezoresistive elements are created by introducing dopant atoms into designated areas of a silicon substrate. *Figure 2.2* illustrates the positioning of piezoresistors on a cantilever beam. In order to accomplish this, dopants such as boron or phosphorus are usually embedded into the silicon lattice by ion implantation or thermal diffusion. The application of stress modifies the band structure by causing a change in the lattice gap between the atoms. The stress dependency of the band structure is responsible for the piezoresistive effect. By establishing a balance between two branches of a Wheatstone bridge circuit, the Wheatstone bridge configuration measures the resistance ⁶⁰.

$$U_{out} = U_{in} \frac{\Delta R_1 + \Delta R_3 - \Delta R_2 - \Delta R_4}{4R} \quad (2.4)$$

In this instance, we employ a Wheatstone bridge configuration, which involves positioning four resistors on the cantilever beam in close proximity to its fixed end ⁵⁸.

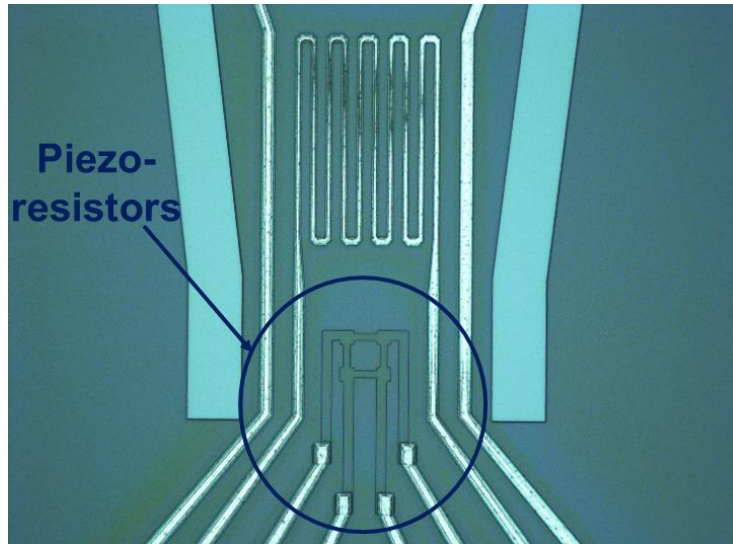


Figure 2.2 Positioning of piezoresistors on a cantilever beam.

When the cantilever bends, mechanical stress is induced along the beam, causing strain at specific locations of the piezoresistive elements. These elements experience a change in resistance proportional to the strain. This behavior is characterized by the

longitudinal (Π_l) and transverse (Π_t) piezoresistive coefficients, which describe the resistance variation in response to stress applied. The resulting resistance variation results in a corresponding change in the output voltage, which can be expressed as:

$$U_{\text{out}} = -U_{\text{in}} \frac{(\Pi_l - \Pi_t)}{2} T_{xx} \quad (2.5)$$

Here, U_{out} is the output voltage, U_{in} is the input voltage, and T_{xx} denotes the applied stress.

The temperature of the measurement and the material doping level affects the piezoresistance. The magnitude of the piezoresistive coefficient has been observed to decrease with increase of doping concentration, and the increase of temperature⁶¹. We employ the ion implantation technique to achieve p⁺ doping. The value of piezoresistors is given by:

$$R = \frac{\rho L}{A} \quad (2.6)$$

while, R is the resistance of each resistor in the Wheatstone bridge, ρ represents the resistivity of doped silicon, L is the length of the resistor, and A represents the cross-sectional area of the resistor.

The structural dynamics of cantilever beams include study of vibration, deformation, and dynamic load response. Following are the few key concepts:

1. Vibrational modes: The cantilever beam vibrates at distinct frequencies, known as natural frequencies. These rely on geometry (length, width, height), material characteristics (young's modulus, density), and boundary conditions of the beam.
2. Mode Shape: Every natural frequency of the beam shows a unique deformation pattern known as mode shape. The first mode is frequently a single bend, whereas higher modes have more complex shapes with additional nodes (points of zero displacement).

When describing the dynamic behavior of micromechanical beams (such as those seen in MEMS devices), a fundamental theory such as Euler-Bernoulli theory are used. The sensors functionality is dependent on the dynamic behavior of micromechanical beams. The beam follows Euler-Bernoulli's theory, a linear theory of elasticity that simply allows us to understand how the beam bends under various load

scenarios ⁶². This model, based on the assumption of small displacements and small thickness compared to the length, was appropriate for analyzing the sensor's response under low excitation levels ⁶³. The deflection in this instance is proportional to the applied load. With this assumption of linear spring constant, the superposition principle is considered ⁵⁶. The assumptions in Euler-Bernoulli Beam theory:

1. Longitudinal axis of the beam remains unchanged.
2. Small deformations (beam's slope and deflection are sufficiently small so that higher-order terms can be neglected).
3. Cross- section of the beam remains planar.
4. Material of the beam is homogeneous and isotropic.

2.1.3 Governing equation

The Euler-Bernoulli beam bending equations are derived based on a set of simplifying assumptions associated with small deformation theory, establishing the linear relationships between forces, moments, and displacements. *Figure 2.3 (a)* shows the side view of a beam deflection, whereby its deflection $w(x)$ is measured as the position of the point in x of neutral axis of the beam relative to its position when the beam is in its neutral undeflected position, and *Figure 2.3 (b)* illustrates the dx sized element of deflected beam.

2.1.3.1 The correlation between strain and displacement

For a section at x , consider a fiber at a distance y from the neutral axis.

Displacement field is given by: i) $w(x)$ = transverse displacement at x , and ii) $u(x, y)$ = axial displacement at x, y .

Assuming pure bending and small deflections, the slope is approximately equal to the angle of rotation. Thus, the relationship between axial and transverse displacement is given by:

$$u(x, y) = -y \frac{\partial w}{\partial x} \quad (2.7)$$

where, $-y \frac{\partial w}{\partial x}$ comes from the rotation of the section beam. $\frac{\partial w}{\partial x}$ is the slope of the neutral axis and y is the vertical distance from the neutral axis

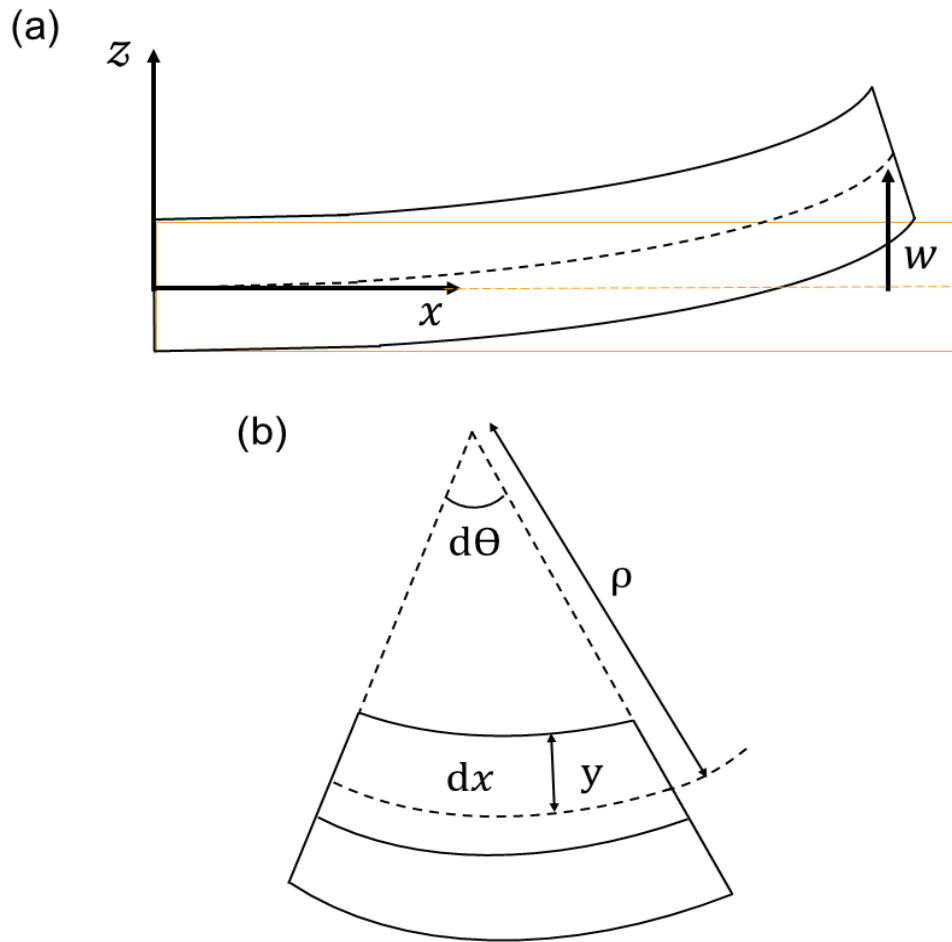


Figure 2.3 (a) Side view of beam deflection (The right end of the beam curves upward by w , measured from the longitudinal neutral axis), and (b) A dx sized element of deflected beam.

2.1.3.2 Longitudinal strain

Longitudinal strain is given as:

$$\epsilon = \frac{\partial u}{\partial x}$$

Substitute $u(x, y)$ from equation (2.7):

$$\epsilon = \frac{\partial}{\partial x} \left(-y \frac{\partial w}{\partial x} \right)$$

$$\epsilon = -y \frac{\partial^2 w}{\partial x^2} \quad (2.8)$$

This implies that strain is proportional to the curvature of the beam, $-\frac{\partial^2 w}{\partial x^2}$, and linearly dependent on y .

2.1.3.3 Stress distribution

Using Hooke's law for linear elastic materials:

$$\sigma = E\epsilon$$

Substitute ϵ from equation (2.8),

$$\sigma = -Ey \frac{\partial^2 w}{\partial x^2} \quad (2.9)$$

This demonstrates how stress varies linearly with distance y from the neutral axis.

2.1.3.4 Moment curvature relationship

The bending moment M is the result of the normal stress distribution across the cross-section. The moment is given by:

$$M = \int \sigma y \, dA$$

Substitute σ from equation (2.9),

$$M = \int \left(-Ey \frac{\partial^2 w}{\partial x^2} \right) y \, dA$$

$$M = -E \frac{\partial^2 w}{\partial x^2} \int y^2 \, dA$$

The second moment of inertia is defined as:

$$I = \int y^2 \, dA$$

Thus,

$$M = -EI \frac{\partial^2 w}{\partial x^2} \quad (2.10)$$

The moment-curvature relationship states that the bending moment is proportional to the curvature of the beam.

2.1.3.5 Equation of beam equilibrium

For equilibrium of forces and moments:

1. The transverse load $q(x)$ relates to the shear force $Q(x)$:

$$\frac{\partial Q}{\partial x} + q(x) = 0 \quad (2.11)$$

2. The shear force $Q(x)$ relates to the bending moment $M(x)$:

$$\frac{\partial M}{\partial x} - Q(x) = 0 \quad (2.12)$$

Substitute $M = -EI \frac{\partial^2 w}{\partial x^2}$ from equation (2.10) into equation (2.12),

$$\frac{\partial}{\partial x} \left(-EI \frac{\partial^2 w}{\partial x^2} \right) - Q(x) = 0$$

If EI is constant:

$$-EI \frac{\partial^3 w}{\partial x^3} - Q(x) = 0$$

From equation (2.11),

$$-EI \frac{\partial^4 w}{\partial x^4} + q(x) = 0 \quad (2.13)$$

This is the Euler-Bernoulli equation.

Table 2.1 presents all the parameters of three sensors, whereas *Figure 2.4* illustrates the geometrical parameters for sensing and tuning part of the beam.

Geometrical parameters (μm)	Sensor 1	Sensor 2	Sensor 3
Sensing part of beam			
Length l_{sp} of the beam	1250	1250	1250
Width w_{0sp} at the beam base	200	200	200
Width w_{1sp} at the beam top	775	775	775
Beam thickness t_{sp} in bending direction	5.8	5.5	5.3
Effective mass (m) in kg	2.80e-9	2.65e-9	2.56e-9
Tuning part of beam			
Length l_{1tp} of the beam	1050	1050	1050
Length l_{2tp} of middle part of the beam	220	220	220
Width w_{tp} of the beam	20	20	20
Beam thickness t_{tp} in bending direction	2.64	2.44	2.39
Resistance R in Ω	13.5	13.5	13.5
Quality factor Q	57	63	64
Spring constants			
Linear spring constant k_{1sp} of sensing beam (N/m)	1.32	1.13	1.00
Linear spring constant k_{1tp} of tuning beam (N/m)	1.76	1.39	1.31
Nonlinear spring constant k_{3tp} of tuning beam (N/m ³)	1.89e11	1.75e11	1.71e11
<i>Table 2.1 Geometrical parameters and spring constants for three different sensors (Note: parameters are given for pure silicon beam).</i>			

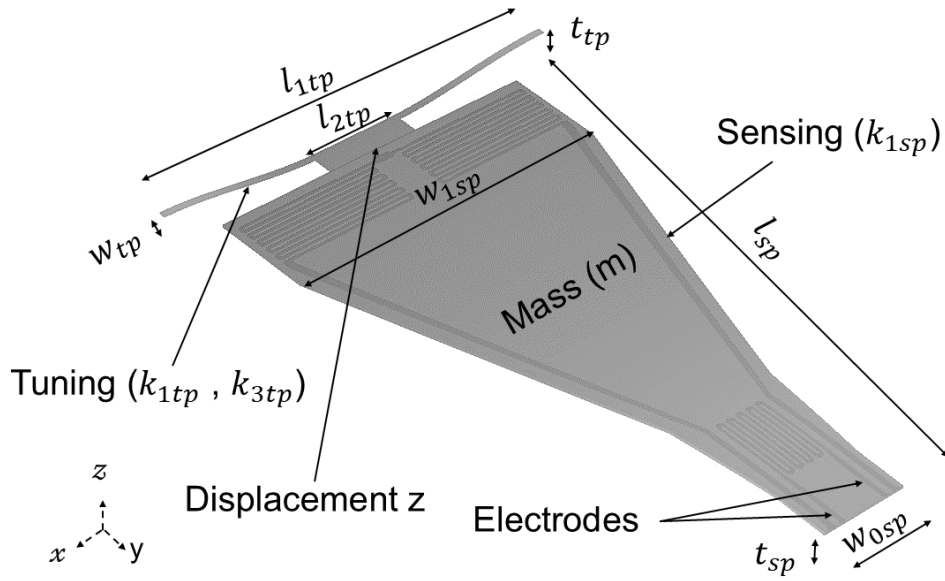


Figure 2.4 Geometrical parameters for sensing and tuning part of the beam, with mass, electrodes and associated spring constants.

2.2 Nonlinearities in a sensor system

Linear behavior is requested in a lot of sensing applications. Linear sensors can detect same noise and signal amplification properties. When considering displacement and noise level, the linear dynamic range of MEMS sensors is considerably limited to small magnitudes ⁶⁴. When micromechanical beams are deflected beyond a certain threshold, the linear theory of elasticity loses validity/is no longer relevant. As a result, the response amplitude of resonant MEMS devices can become very large, leading to nonlinear behavior, and thus linear approximations are insufficient to accurately anticipate their behavior. The relationship between system excitation and response provides a general indication of whether the system will operate linearly or nonlinearly⁶⁵.

The human cochlea responds to sound in a nonlinear way. In cochlea, small sounds are amplified a lot, while loud sounds are amplified less, or even compressed. Here, we are primarily interested in mimicking the functionality, therefore nonlinear behavior is essential for this work to achieve the major advantages such as high sensitivity, frequency selectivity, compression and amplification, dynamic range control and so on. Furthermore, nonlinear sensors can provide a wide dynamic range while recording the noisy environment and signal amplification ⁶⁶. The dynamics of hair cells in the inner ear play a key role in how we hear different sounds. These cells employ nonlinear

amplification, which implies that they do not respond in a linear, predictable way. For example, a higher sound level suppresses a signal to a lower level, whereas the lower sound level amplifies a higher level of signal. This behavior is an example of nonlinear sensing, in which the sensor's response varies with the input level. Such nonlinear behavior exists in biological systems, and is increasingly being used as inspiration for bio-inspired sensor designs that can adapt to varying signal levels, just as our ears do⁶⁷. We thereby extend the linear model to nonlinear ones. The subsequent sections discuss nonlinear models.

Given the dynamic response of micro-sensors, nonlinearities may emerge due to their small size as well as damping and stiffness factors^{68–70}. The nonlinear dynamics of MEMS sensors can be exploited to achieve better sensing performance. For example, Rhoads et al.,⁷¹ demonstrated how nonlinearities can be employed to improve MEMS sensor sensitivity and operational bandwidth by tuning resonance properties. Donghao Li et al.,⁷² investigated the nonlinear tuning of MEMS vibratory rate gyroscopes, and demonstrated showing how the use of non-uniform DC biases can improve rate sensitivity. Furthermore, studies on how to tune the nonlinearity of MEMS have been presented, by Westra et al.,⁷³ investigated nonlinear modal coupling in clamped-clamped resonators, or Li et al.,⁷⁴ who illustrated how strain can be applied to fine-tune the nonlinearity in MEMS beams.

Nonlinearities in beam can often be introduced by the following ways:

1. **Material nonlinearities:** These arise when the material does not exhibit a linear stress-strain relationship. Large strains can cause changes in the mechanical properties of the material, resulting in a nonlinear response even if the geometry remains unchanged⁷⁵.
2. **Geometric nonlinearities:** These arise from large deflections in the structure. Geometric nonlinearity occurs, when a microbeam sensor oscillates with a large amplitude in relative to its thickness⁷⁶. This type of nonlinearity is independent of the material and becomes dominant even when the deformations are moderate. However, the geometry no longer follows small-angle or small-displacement assumptions⁷⁷ (see *Figure 2.5 (a)*). To estimate the large deflection solution of micromechanical beams, it is essential to incorporate the coupling between the transverse and axial motion, which

introduces the concept of geometric nonlinearity (see *Figure 2.5 (b)*). In this work, geometric nonlinearities are taken into consideration.

This is because the sensor structures investigated here operate under conditions where the displacements are large compared to thickness. As a result, MEMS structures exhibit geometric nonlinearities. The frequency can be modified by applying an external static force (by augmenting strain on the beam), which would elongate the beam and thus alter its natural frequency response. This external force is induced by a static direct current voltage.

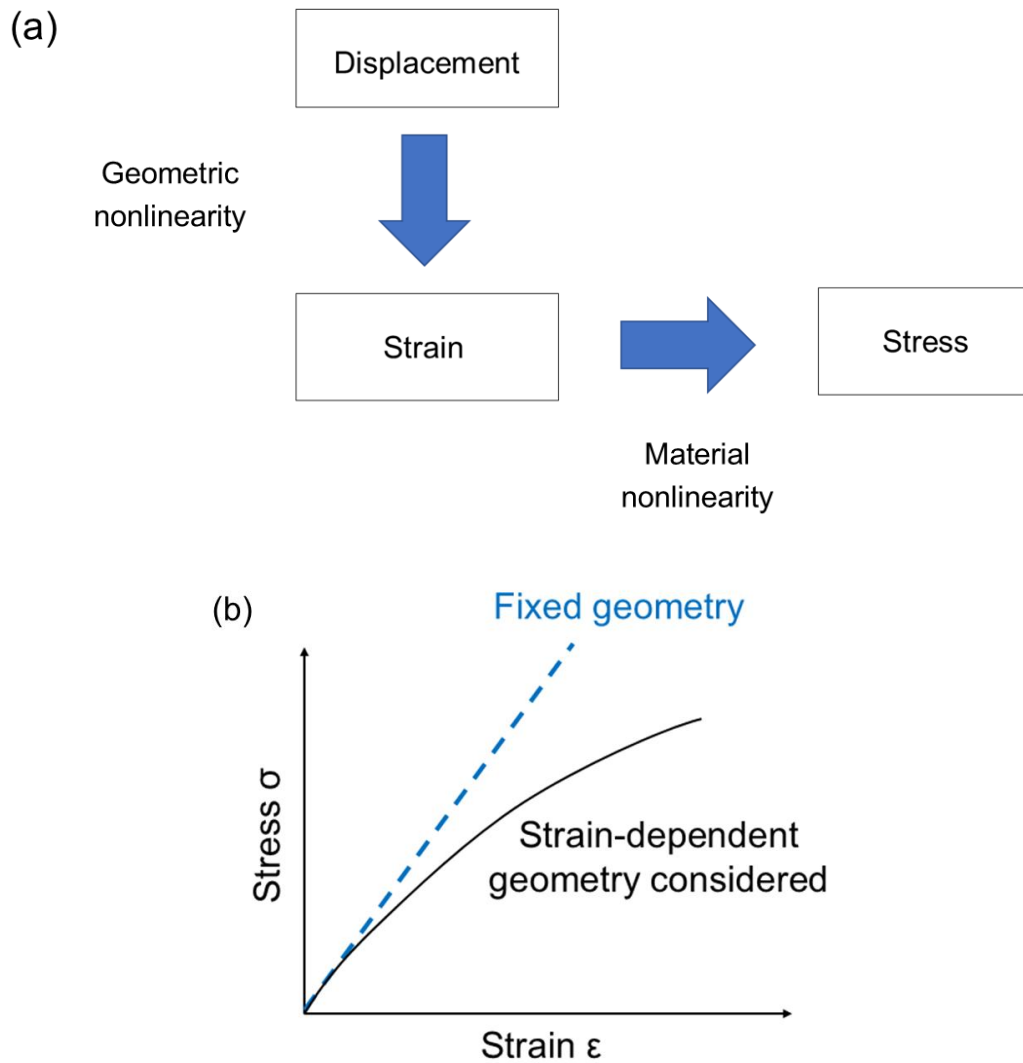


Figure 2.5 Nonlinearity characteristics of MEMS sensors: (a) Geometric nonlinearities (strain-dependent), and Material nonlinearities (stress-dependent), (b) In our case, strain-dependent geometry (geometric nonlinearities) is considered.

However, to accurately capture the sensor's nonlinear response under higher excitation levels or larger displacements, we extended this model with a Duffing-type

nonlinear term. The Duffing model have been chosen because it can account for the nonlinear stiffness characteristics observed at higher response amplitudes, as explained in the following section.

2.3 Non-linear oscillator: Duffing

The sensor can be modelled as spring-mass system with an additional nonlinear spring (see *Figure 2.6*). Consequently, the system resembles a Duffing oscillator. The defining feature of a Duffing oscillator is the presence of nonlinear stiffness, commonly represented by a cubic stiffness term. The Duffing model is a mathematical model used to describe dynamics of nonlinear oscillatory systems. It extends the classical linear harmonic oscillator by introducing this nonlinear term ^{78,79}.

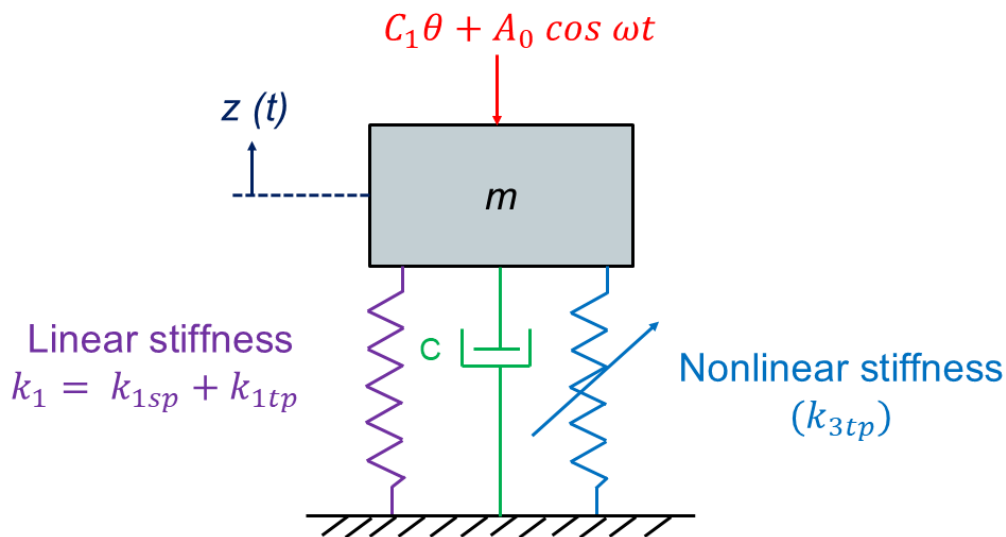


Figure 2.6 Lumped model of spring-mass model demonstrating mass is in parallel combination with dashpot c , linear stiffness (k_1) and nonlinear stiffness (k_{3tp}).

In this work, the Duffing model is employed to describe the nonlinear dynamic behavior that cannot be described by linear models. These include amplitude-dependent resonance, in which the resonance frequency shifts with an increasing oscillation amplitude. Additionally, it accounts for phenomena such as spring hardening, in which the resonance frequency increases with oscillation amplitude, and spring softening, in which it decreases. The term spring hardening and spring softening refers to the changes in the effective stiffness of a nonlinear system under oscillatory motion, which is common in mechanical, structural, and material systems ⁸⁰. *Figure 2.7* shows the

frequency response curve of the nonlinear oscillator, which highlights the characteristic Duffing response.

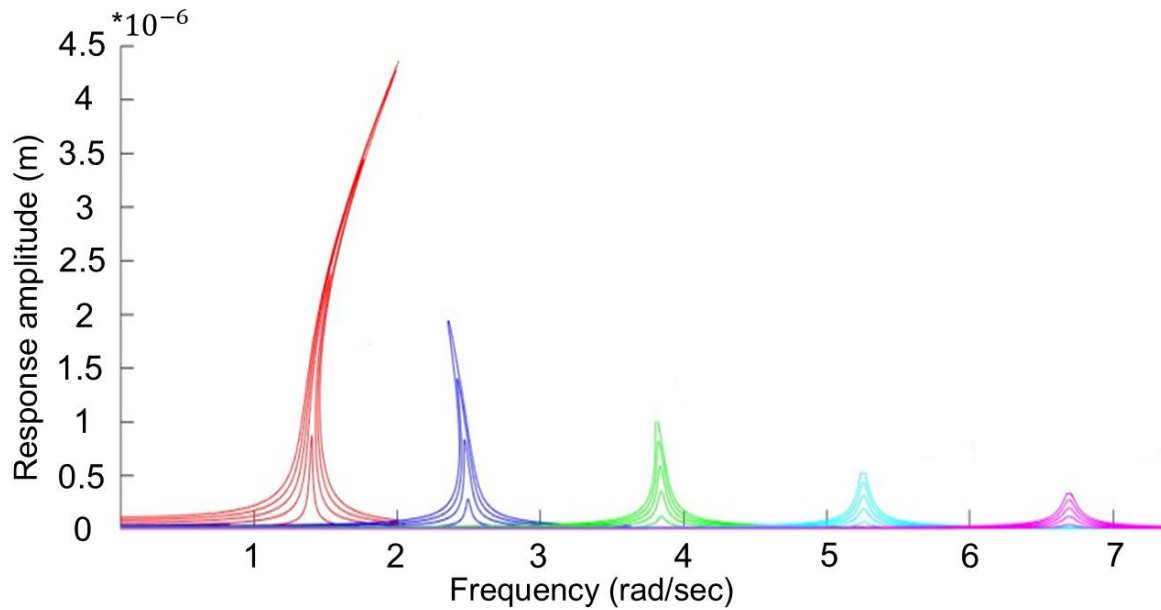


Figure 2.7 Frequency response curve of the nonlinear oscillator showing the characteristic Duffing response.

2.3.1 Spring hardening

Spring hardening is a phenomena, in which the effective stiffness of a system increases with the amplitude of oscillation. This leads to an upward shift in the natural frequency at higher amplitudes. This phenomenon arises when the cubic stiffness term k_{3tp} is positive, resulting in an increased restoring force and displacement. In this case, the spring becomes stiffer with higher displacement, indicating hardening behavior. This can occur in the Duffing oscillator when there are large-amplitude oscillations. The cubic nonlinearity term k_{3tp} of the system causes the stiffness to rise, thus require greater forces for further displacements.

2.3.2 Spring softening

The opposite of spring hardening is spring softening, occurs when the effective stiffness decreases with the amplitude of oscillation. This causes a decrease in the natural frequency at higher amplitudes. This occurs when the cubic stiffness term k_{3tp} is negative, resulting in a decrease in restoring force with increasing displacement. In this case, the spring becomes softer with higher displacement, indicating softening behavior. In this instance, the system may be prone to instability and may experience

bifurcations, where small variations in parameters can cause significant changes in the behavior of the system. The nonlinear nature of the Duffing oscillator serves as an excellent illustration of how a system can exhibit both hardening and softening phenomena ⁸¹.

2.3.3 Dynamics of the sensor system (Duffing equation and explanation of terms)

The dynamics of the sensor system, as illustrated in *Figure 2.4*, are modeled using the two equations (equation 2.14 and equation 2.15) for single degree of motion ²³ to incorporate the Duffing-like nonlinearity. A Duffing-like nonlinearity refers to a system behavior where the restoring force includes not only a linear term proportional to displacement, as in simple spring, but also a nonlinear stiffness term, typically a cubic term that captures amplitude-dependent behavior.

$$m\ddot{z} + C\dot{z} + k_1z + k_{3tp}z^3 = C_1\theta + A_0 \cos \omega t \quad (2.14)$$

$$\dot{\theta} + \tau^{-1}\theta = C_2 \left(\frac{U^2}{R} \right) \quad (2.15)$$

In this context, m represents the effective mass, C denotes the damping coefficient, $k_1 = k_{1sp} + k_{1tp}$ defines the linear spring constant, depending on the spring constants k_{1sp} of the sensing part and k_{1tp} of the tuning part, respectively. Additionally, k_{3tp} signifies the higher order stiffness parameter of the tuning part. *Equation 2.14*, and *2.15* are based on well-known theoretical models, as discussed by Younis ⁸², Kovacic and Brennan ⁸³, and Rand ⁸⁴. *Equation 2.14* describes the beam displacement z (at the end of sensing part) as a response to a harmonic force with amplitude A_0 and frequency ω , and the temperature difference of the beam with the surrounding/mounting θ (due to the bimorph effect). *Equation 2.15* describes the thermal response of the beam, i.e., the change of the beam temperature resulting from an applied voltage U . C_1 and C_2 denotes the transfer factors, respectively, from temperature to deflection, and from voltage to temperature, R represents the resistance of the actuator, and τ signifies the time constant for temperature variations.

The objective of this design is to enable the tuning of resonance frequency without tilting the resonance curve. A tilted curve makes it more difficult to precisely detect the resonance peak and can alter the Q-factor calculation. To avoid this, the actuation

voltage is kept within the safe range, ensuring consistent and reliable sensor performance⁸⁵. Consequently, the oscillation amplitude shall be significantly smaller than the static deflection and the DC deflection is used to achieve the frequency tuning. Therefore, considering the pre-deflection, the origin of the coordinate system must be shifted to position z_0 (working point) using the transformation $\hat{z} = z - z_0$. In this context, the term pre-deflection refers to the initial static deflection of the system due to a constant force or load. Shifting the coordinate system to this new equilibrium point facilitates the analysis of the system's dynamic behavior. Thus, equation 2.14 has to be modified and the following governing equation of motion at the driving frequency is obtained:

$$\ddot{\hat{z}} + 2\zeta\omega_0\dot{\hat{z}} + \alpha\hat{z} + \beta\hat{z}^2 + \gamma\hat{z}^3 = \frac{C_1}{m}\theta + A_0/m \cos \omega t \quad (2.16)$$

where, $\alpha = \frac{k_1 + 3z_0^2 k_{3tp}}{m}$, $\beta = 3z_0 k_{3tp}/m$, $\gamma = k_{3tp}/m$ represent the linear, quadratic, and cubic nonlinear system parameters respectively; $\zeta = \frac{c}{2\sqrt{\alpha}m}$ denotes the damping ratio; and A_0/m signifies the amplitude of the driving force per unit mass. The important prefactor to consider for our beam design is the system parameter α , since it is responsible for determining the frequency response ($\omega_0 = \sqrt{\alpha}$). Consequently, the value of $3z_0^2 k_{3tp}$ must be comparable with k_{1sp} to induce a modification in resonance frequency. Note, z_0 is a function of the DC actuation voltage U_{dc} .

A C-C beam with a point load at the centre of beam is considered to determine when its deflection becomes significant in relation to its thickness (see *Figure 2.8*). The strain energy effects, such as bending and stretching, must be considered as we allow for larger deflection⁵⁶. Moreover, it is evident that the stiffness of the beam increases with increasing deflection. When the deflection exceeds the beam thickness, the stretching component begins to dominate over the bending term. Both transverse deflection $w(x)$ and axial deflection $u(x)$ are considered, when the beam experiences larger deformation.

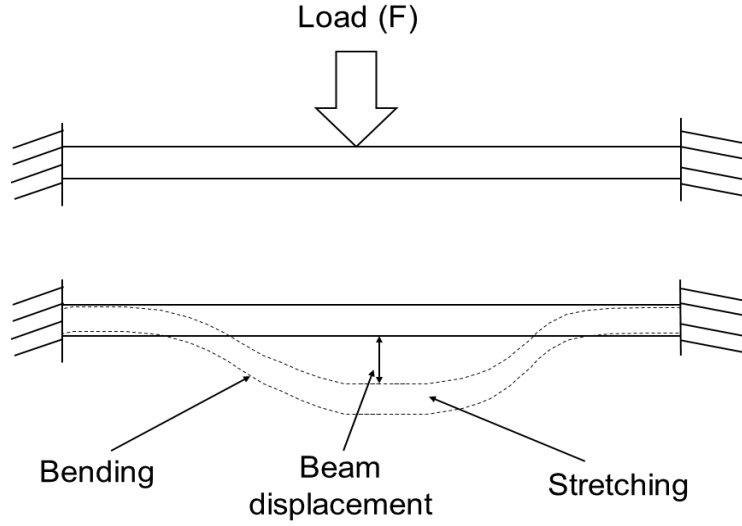


Figure 2.8 Schematic representation showing clamped-clamped micromechanical beam.

The deformed length is determined by:

$$ds = \sqrt{(dx + u(x+dx) - u(x))^2 + (w(x+dx) - w(x))^2} \quad (2.17)$$

To further simplify,

$$ds = dx \left(1 + \frac{du}{dx} + \frac{1}{2} \left(\frac{dw}{dx} \right)^2 \right) \quad (2.18)$$

The axial strain is determined by:

$$\epsilon_x = \frac{ds - dx}{dx} \quad (2.19)$$

Thus,

$$\epsilon_x = \frac{du}{dx} + \frac{1}{2} \left(\frac{dw}{dx} \right)^2 \quad (2.20)$$

The total change in length can be computed as:

$$\delta l = \int_{-l_{tp}/2}^{l_{tp}/2} \epsilon_x dx \quad (2.21)$$

The axial strain of the original neutral axis: $\epsilon_a = \frac{\delta l_{tp}}{l_{tp}}$

$$\epsilon_a = \frac{1}{l_{tp}} \int_{-l_{tp}/2}^{l_{tp}/2} \left(\frac{du}{dx} + \frac{1}{2} \left(\frac{dw}{dx} \right)^2 \right) dx \quad (2.22)$$

The integral equation can be solved as follows:

$$\epsilon_a = \frac{1}{l_{tp}} \left(u \left(\frac{l_{tp}}{2} \right) - u \left(-\frac{l_{tp}}{2} \right) \right) + \frac{1}{l_{tp}} \int_{-l_{tp}/2}^{l_{tp}/2} \frac{1}{2} \left(\frac{dw}{dx} \right)^2 dx \quad (2.23)$$

The first term within the bracket is zero due to the beam being fixed at both ends. Here, the equation simply considers the second term which becomes:

$$\epsilon_a = \frac{1}{l_{tp}} \int_{-l_{tp}/2}^{l_{tp}/2} \frac{1}{2} \left(\frac{dw}{dx} \right)^2 dx \quad (2.24)$$

Additionally, we examined the variational approach analysis during which the beam follows principle of superposition. Total deformation has two phases: bending and stretching of the beam.

The total axial strain can be expressed as:

$$\epsilon_T = \epsilon_{stretching} + \epsilon_{bending} \quad (2.25)$$

$$\epsilon_T = -z \frac{d^2w}{dx^2} + \frac{1}{l_{tp}} \int_{-l/2}^{l/2} \frac{1}{2} \left(\frac{dw}{dx} \right)^2 dx \quad (2.26)$$

The total strain energy can be determined from:

$$W = \frac{E_{wtp}}{2} \int_{-t_{tp}/2}^{t_{tp}/2} \int_{-l_{tp}/2}^{l_{tp}/2} \epsilon_T^2 dx dz \quad (2.27)$$

The work done by the external load is denoted as F_c . The potential energy is therefore given by:

$$U = \frac{E_{wtp} t_{tp} \pi^4 (8 t_{tp}^2 + 3 z_0^2) z_0^2}{96 l_{tp}^3} - F_c \quad (2.28)$$

Taking the derivation with respect to z_0 and setting the result to zero provides the spring constants for the tuning part from the static deflection z_0 of a C-C beam:

$$F = \left(\frac{\pi^4}{6} \right) \left(\frac{E_{wtp} t_{tp}^3}{l_{tp}^3} \right) z_0 + \left(\frac{\pi^4}{8} \right) \left(\frac{E_{wtp} t_{tp}}{l_{tp}^3} \right) z_0^3 \quad (2.29)$$

The equation indicates that the first term is a small deflection bending term, proportional to z_0 and describes the linear spring constant k_{1tp} . Whereas the second term is a stretching term, proportional to z_0^3 and reflecting the nonlinear spring

constant k_{3tp} . The relationship between the applied load and the resulting deflection is nonlinear. As can be seen, thicker beams tend to be primarily dominated by the bending term, while thinner beams are more significantly affected by the stretching term.

Based on these theoretical considerations, the design parameters can be modified in the following ways. The length and thickness of sensing part are kept larger than those of tuning part. In this case, the natural resonance frequency of the sensor is mostly determined by geometrical aspects of the sensing part without attaching the tuning part to understand the behavior of sensing part is given by ²⁴:

$$f = \frac{\omega_0}{2\pi} = \delta_n^2 \frac{t_{sp}}{2\pi l_{sp}^2} \sqrt{\frac{E}{12\rho}} \quad (2.30)$$

where, δ_n is the pre-factor for the nth mode, t_{sp} is the thickness of the beam, l_{sp} is the length of the beam, E is the modulus of elasticity and ρ is the density of silicon, respectively ²⁴.

Moreover, the parameters of tuning part must be determined to avoid altering the resonance frequency of sensing part and give the desired nonlinearity. The length of tuning part is selected based on equation 2.29 to attain the desired value of cubic nonlinearity. The thickness of tuning part (t_{tp}) is chosen to be between 2 μm to 3 μm in order to keep the linear stiffness of tuning part in proximity to that of sensing part. Hence, the length and thickness of the beam are crucial factors we have considered here, with the beam's thickness being more readily adjustable to tune the properties.

CHAPTER 3

FINITE ELEMENT MODELLING APPROACH AND ASSUMPTIONS IN DEVELOPING BIO-INSPIRED ACOUSTIC MEMS SENSOR

3.1 Finite element modelling using COMSOL Multiphysics

This chapter presents the finite element modeling (FEM) and key assumptions used to evaluate and validate the design of the proposed bio-inspired acoustic MEMS sensor. To analyze its physical behavior, a multiphysics FEM model have been developed using COMSOL Multiphysics. The finite element method is used to support analytical studies and investigate the nonlinear response of silicon micro-beams. *Figure 3.1* illustrates the dynamic modelling workflow used in the development of the MEMS sensor using COMSOL. As shown, the process begins with defining key inputs such as material properties, relevant multiphysics module interfaces, and fabrication-related parameters. Afterward, the sensor geometry is imported into COMSOL. A multiphysics simulation is then performed, coupling mechanical, thermal and electrical domains as needed. The simulation results are compared with experimental data to validate the accuracy of the model.

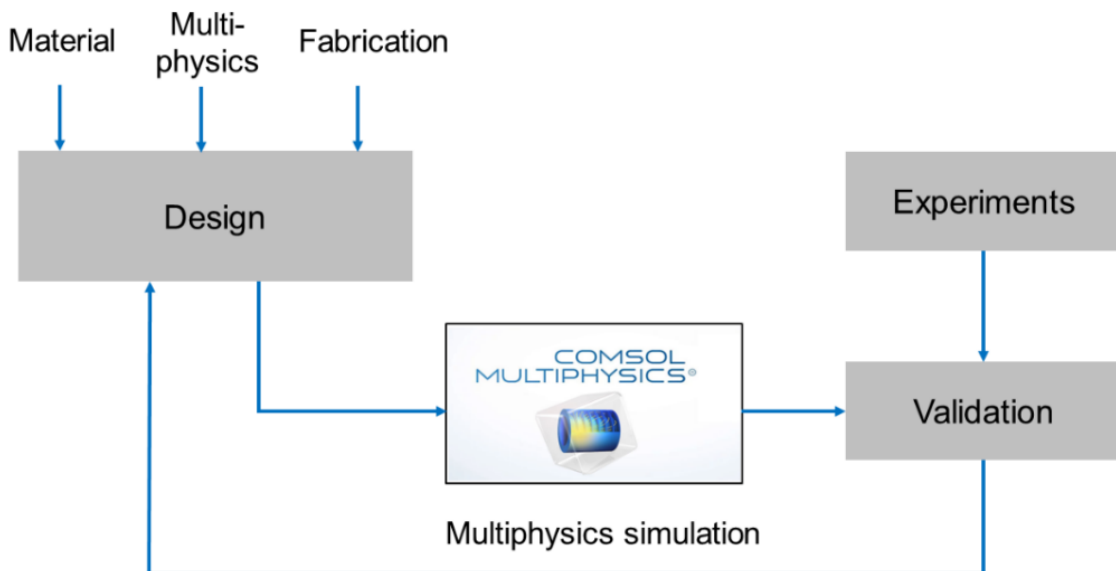


Figure 3.1 COMSOL multiphysics dynamic modelling approach in developing the bio-inspired MEMS sensor.

3.2 Dynamic modelling approach and testing of geometric nonlinearity

The physical behavior of sensor has been modeled in COMSOL utilizing a step-by-step process. The main steps are listed below:

1. Problem definition and physics selection: The sensor is inspired by biological auditory systems and operates based on the mechanical response of microstructures. To study how the proposed sensor behaves under different conditions, a multiphysics simulation has been carried out using COMSOL Multiphysics 6.0. To simulate this behavior accurately, the physics interfaces have been used. The model includes several key physics interfaces:

- Solid Mechanics: to determine stress, strain, and how the structure deforms.
- Electric Currents: to simulate DC current flow and how it causes Joule heating.
- Heat Transfer in Solids: to calculate temperature changes and heat distribution.

These interfaces help simulate the response of sensor when DC voltage is applied (up to 600 mV), including heat generation, temperature increase, and mechanical displacement.

2. Geometry construction: The sensor geometry is created in the KLayout design tool. After defining the model geometry, it is exported in GDS format and subsequently imported into COMSOL Multiphysics 6.0 for further simulation and analysis (refer *Figure 3.2*).

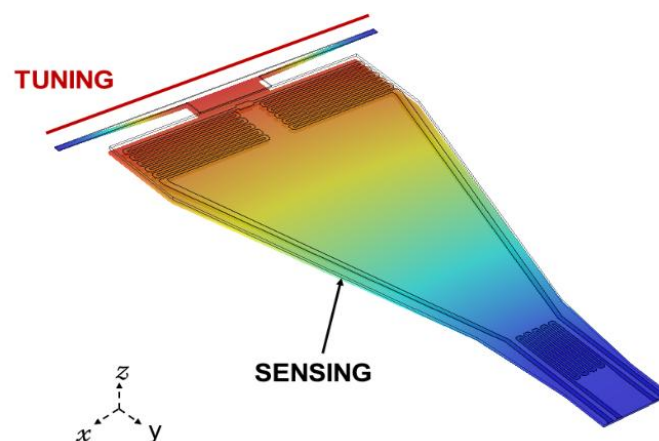


Figure 3.2 FEM model of bio-inspired MEMS sensor showing sensing part, and tuning part (clamped-clamped micromechanical beam).

3. Material properties: The proposed sensor incorporates key input parameters, including material selection (for example, Silicon (Si), and Aluminium (Al)) and their respective physical properties. These include:

- Density: Si - 2329 kg/m³, Al - 2694 kg/m³
- Thermal conductivity: Si - 131 W/(m*K), Al - 236 W/(m*K)
- Young's modulus: Si - 170 GPa, Al - 70 GPa
- Coefficient of thermal expansion: Si - 2.6×10^{-6} (1/K), Al - 23.3×10^{-6} (1/K)).

4. Boundary and initial conditions: The domain parameters are carefully defined, and the boundary conditions are applied according to the sensor's geometry i.e., both ends of clamped-clamped beam are fixed, cantilever near the end side are kept fixed.

5. Meshing and solver type selection: A physics-controlled mesh is applied to the domains, including refinement in critical regions. It is used to discretize the domain, with a finer mesh size chosen based on convergence analysis. Mesh convergence studies are performed to verify mesh quality. The final mesh consists of 179368 domain elements, 0.5523 average element quality, 101318 boundary elements, mesh vertices 52280, mesh volume 3620000 μm^3 , and 12471 edge elements. Mesh size is determined through mesh convergence analysis, ensuring the optimal element size for the simulation. Finally, the solver is configured based on the type of analysis and the desired output precision.

6. Study configuration: To analyze the operational aspects of the sensor, the following studies are conducted:

- Stationary study: to analyze the steady-state behavior of sensor under applied DC voltage.
- Eigenfrequency study: to determine the sensor's natural vibration modes and their corresponding resonance frequencies, crucial for understanding dynamic performance.

Finally, the results, including the displacement amplitudes of the beam have been plotted. Further details about these modules and study types, including the boundary conditions, is explained in the following sections.

3.3 Solid Mechanics Interface

The solid mechanics interface in COMSOL is used to study how solid structures respond to various loads, such as forces, thermal effects, and boundary constraints. It allows for the simulation of displacement, strain, and stress distributions in both elastic or nonlinear materials ⁸⁶. The solid mechanics interface is used in this work to calculate displacements/deformations, as well as dynamic characteristics including natural frequencies and mode shapes. This step is important in the simulation, since the sensor's mechanical response, such as deflection and resonance, is directly related to its functionality and sensitivity. Appropriate boundary conditions have been applied, such as fixing both ends of clamped-clamped beam and fixing the cantilever near the end.

3.4 Electric Current Interface

The electric currents interface in COMSOL is used to model the distribution of electric potential, current density, and Joule heating when a DC voltage is applied ^{87,88}. In this work, it is used to simulate a heater element that is subjected to an external voltage of up to 600 mV. The boundary conditions include applying an electric potential to one end of the heater and grounding the other end, allowing the current to flow. The applied voltage creates a potential difference that drives current through the metal. As current flows, it generates heat, which is automatically coupled to the heat transfer in solids interface. This analysis is important for understanding how the applied voltage leads to a temperature change, that affects the mechanical behavior of the sensor.

3.5 Heat Transfer in Solids Interface

The heat transfer in solids interface is used to model both steady state and transient heat conduction in solid materials ⁸⁷. It is useful for analyzing MEMS devices in which temperature influences affect mechanical or electrical behavior. In this work, the interface is used to calculate the temperature distribution in the structure due to Joule heating. This temperature field is then passed to the solid mechanics interface to account for thermal expansion. The simulation captures temperature differences across silicon (Si) and aluminum (Al) regions, which are important because mismatches in their thermal expansion coefficients cause bending. This step is essential for understanding how electrical input leads to mechanical deformation

through thermal effects. Boundary conditions have been applied by fixing the temperature on selected surfaces, and the initial temperature of the domain has generally set to ambient, or 293.15 K.

3.6 Stationary study

The stationary study in COMSOL Multiphysics is used to analyze the response of the sensor under steady-state conditions, where the time-dependent effects are not significant⁸⁷. In this work, stationary study is used to simulate how the sensor behaves under constant DC voltage. This includes evaluating how electric current causes steady Joule heating, how the temperature distributes across the sensor, and how the resulting temperature rise leads to thermal expansion and structural deformation. Because the voltage and other conditions remain constant, a steady-state analysis is suitable. The results from this study helps us understand how the sensor performs during continuous operation, as well as how factors such as geometry and material properties affect temperature rise and displacement.

3.7 Eigen frequency study

The eigen frequency (or natural frequency) of a sensor refers to the specific frequency at which its mechanical structure naturally tends to vibrate. At each of these frequencies, the sensor deforms into a particular pattern, called a mode shape. In this work, the eigenfrequency study in COMSOL Multiphysics is used to analyze the dynamic behavior of the sensor's mechanical structure. This includes identifying its natural frequencies and observing how the structure deforms at those frequencies⁸⁹.

This analysis serves three main purposes:

1. Identifying resonance frequencies to avoid unwanted resonances that could affect stability or accuracy.
2. Visualizing mode shapes, which show how different parts of the sensor move during vibration.
3. Supporting design improvements by adjusting geometry or material properties to shift the resonance frequencies as needed.

To account for the effect of thermal loading on the sensor's dynamic behavior, a prestressed eigenfrequency analysis is performed. This involves two steps: First, a

stationary (steady-state) study is run to calculate the thermal and mechanical stresses caused by the thermomechanical bimorph effect. Then, the eigenfrequency study is run on the prestressed structure to determine vibration modes and frequencies under realistic loading conditions. It is important to note that the eigenfrequency study only provides the natural frequencies and mode shapes; it does not calculate the actual vibration amplitudes. For that, a frequency domain study is required, which requires proper loading and dissipation parameters. *Figure 3.3* provides a flowchart of COMSOL Multiphysics simulation platform, which includes the input information and boundary conditions.

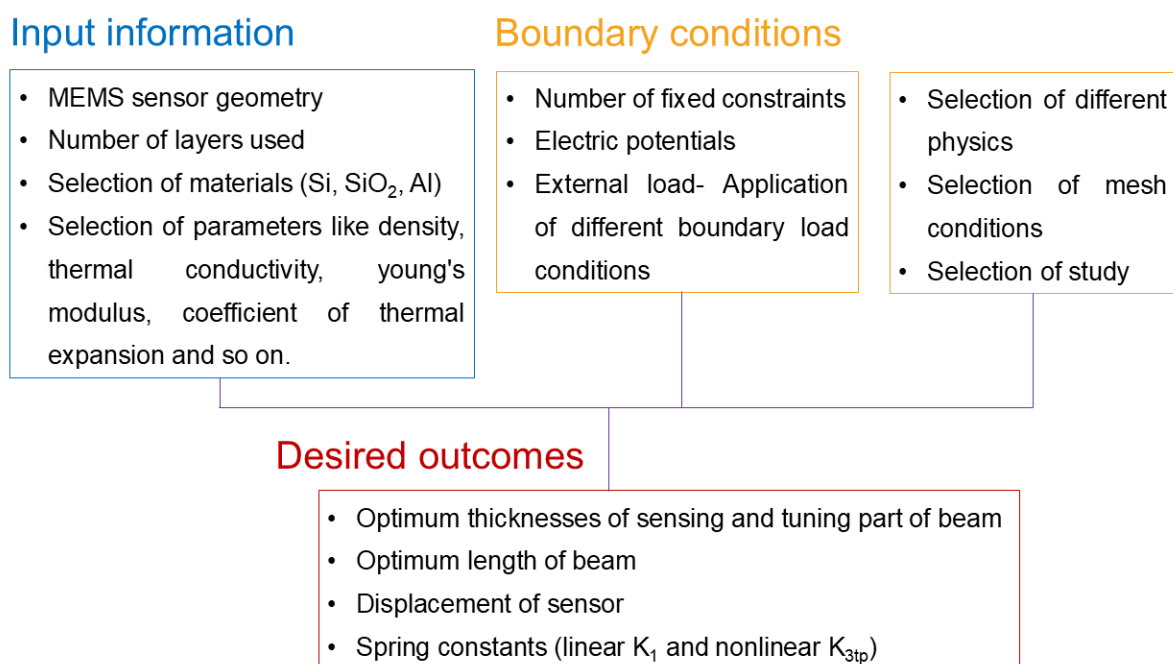


Figure 3.3 Flowchart of COMSOL Multiphysics simulation platform, which includes the input information and boundary conditions.

3.8 Validation and nonlinearity assessment

To evaluate the mechanical performance of sensor and examine its nonlinear behavior, a series of simulations have been performed using COMSOL Multiphysics. These simulations aimed to investigate the bending behavior of the microbeam structure under various point load conditions. In the simulation, a point load has applied to the sensing part of the microbeam. *Figure 3.4* shows the COMSOL multiphysics finite element simulations illustrating the displacement when a point load is applied at the center of the beam for (a) the sensing part, and (b) the tuning part.

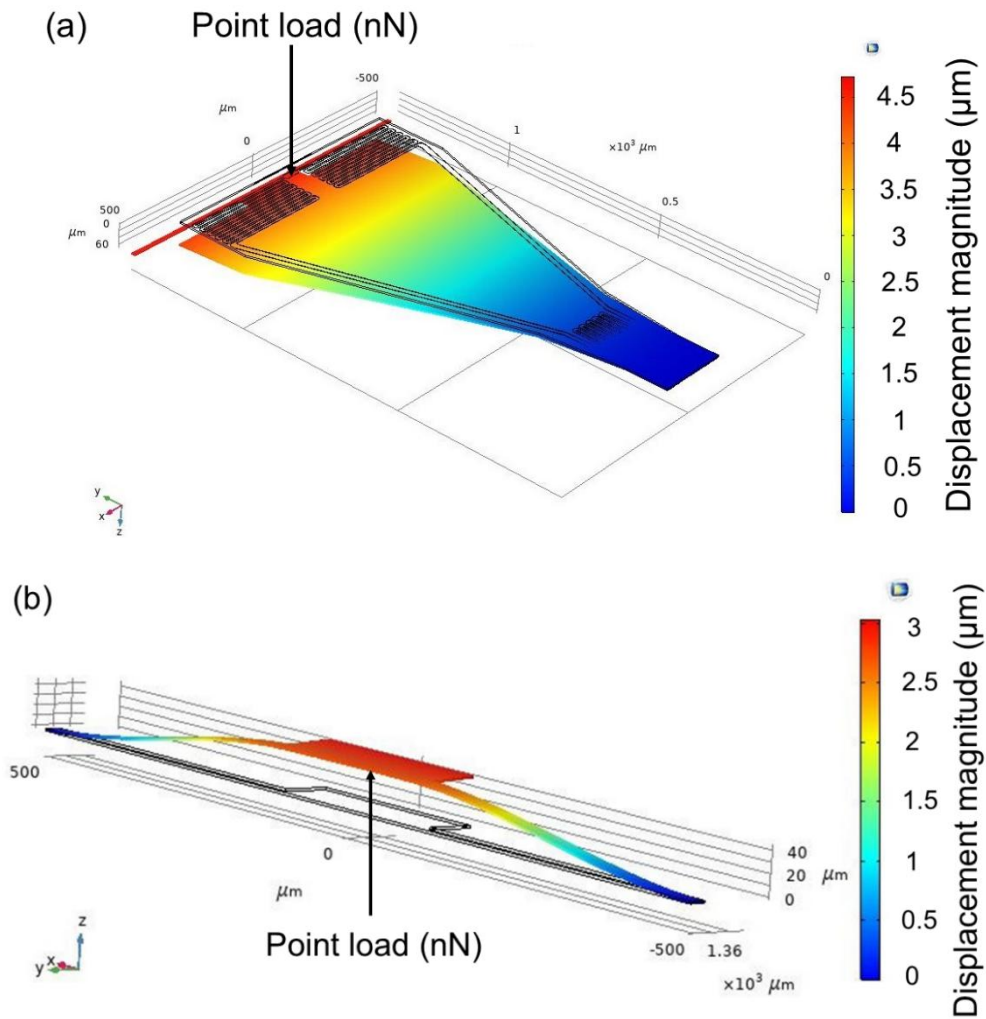


Figure 3.4 COMSOL multiphysics finite element simulations illustrating the displacement when a point load is applied at the center of the beam for (a) the sensing part, and (b) the tuning part.

The applied load have been gradually increased in steps, starting from 100 nanonewtons (nN) and reaching up to 7000 nN (as summarized in *Tables 3.1, 3.2, and 3.3*). At each load step, the corresponding displacement have been recorded to create a load applied-displacement curve. This curve is then used to assess whether the sensor exhibited a linear or nonlinear mechanical response. *Table 3.1, 3.2, and 3.3* present the displacement values corresponding to various point loads applied for the sensing part, tuning part, and combined sensing and tuning part of the sensor.

Sr. No	Load applied (nN)	Displacement (μm)
1	100	0.07
2	200	0.13
3	400	0.26
4	600	0.39
5	800	0.53
6	1000	0.66
7	2000	1.31
8	3000	1.97
9	4000	2.63
10	5000	3.28
11	6000	3.94
12	7000	4.6
<i>Table 3.1 Displacement values under various point loads applied to the sensing part of the beam.</i>		

Sr No	Load applied (nN)	Displacement (μm)
1	100	0.065
2	200	0.13
3	400	0.25
4	600	0.38
5	800	0.5
6	1000	0.65
7	2000	1.2
8	3000	1.8
9	4000	2.2

10	5000	2.6
11	6000	2.9
12	7000	3.2
<i>Table 3.2 Displacement values under various point loads applied to the tuning part of the beam.</i>		

Sr No	Load applied (nN)	Displacement (μm)
1	100	0.06
2	200	0.127
3	400	0.254
4	600	0.379
5	800	0.502
6	1000	0.621
7	2000	1.165
8	3000	1.62
9	4000	2.004
10	5000	2.336
11	6000	2.631
12	7000	2.896
<i>Table 3.3 Displacement values under various point loads applied to the combined sensing and tuning parts of the beam.</i>		

The simulation results show how the sensing part of the beam responds to an externally applied point load. Using the solid mechanics interface, the displacement is calculated for different load values. These results are used to plot a displacement-versus-load graph. The graph shows a straight line for the sensing part of the beam, confirming that the response is linear (see *Figure 3.5*). This linear behavior is valid as long as the material stays within its elastic limit and the deformations are small enough that geometric nonlinearities do not occur. The same approach is then used for the

tuning part, followed by the combined sensing and tuning parts of the beam. The results showed that, unlike the sensing part, the tuning part displays nonlinear behavior. This curved shape confirms that the load-displacement graph does not form a straight line (see *Figure 3.5*). The nonlinearity is caused by geometric effects, where large deformations make the beam either stiffer or more flexible as it bends.

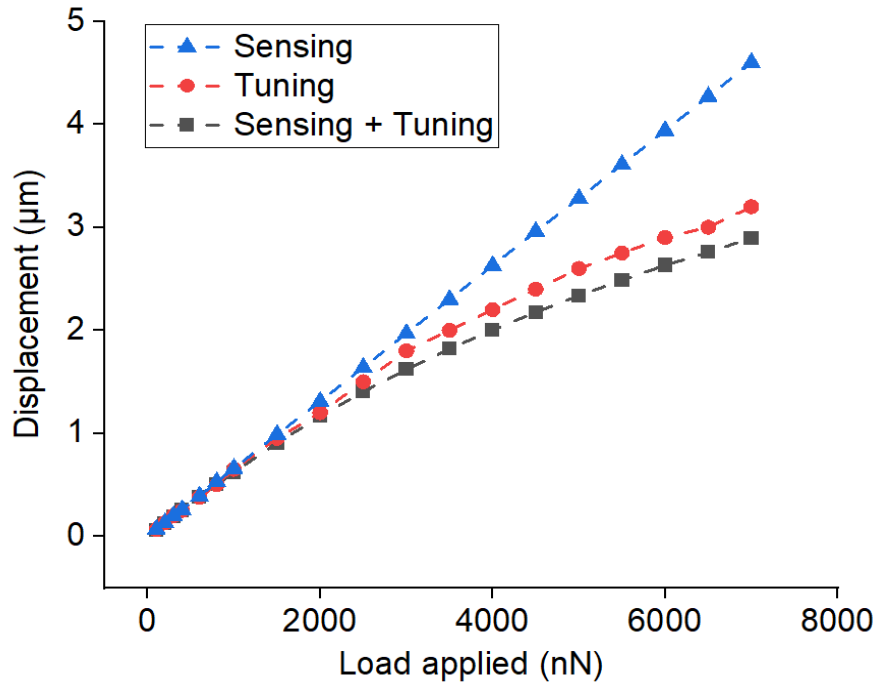


Figure 3.5 Displacement response curves under various applied load circumstances for the corresponding sensing, tuning and combination of sensing and tuning part respectively.

The displacement for the tuning part, and the combined sensing and tuning part is estimated to be 3.2 μm and 2.89 μm respectively (see *Figure 3.5*). The displacement values provide insights about the mechanical behavior of sensor under applied loads. The tuning part experiences a displacement of 3.2 μm , while the combined sensing and tuning parts together experience a displacement of 2.89 μm . These displacements show how much each part of the sensor deforms under the applied conditions. The tuning part experiences slightly more displacement than the combined setup, implying that the combination of the two parts affects how they bend together. Furthermore, the multi-physics optimization method utilizing COMSOL Multiphysics is then executed to ascertain the geometrical parameters of the cantilever and resonance frequency. The dimensional parameter, such as the thickness of its C-C beam of the sensor have been optimized. The thickness value is optimized by varying it from 2.75 μm to 6.75 μm ,

respectively. When considering the geometric nonlinearity, the incorporation of C-C beam helps in achieving the microbeam nonlinearity and alters the dynamics of softening/ hardening phenomenon. The nonlinear response is essential for tuning the sensor's resonance frequency, which is vital for covering the broader frequency ranges in a single beam.

The nonlinear effects of sensor beam result in spring hardening or softening phenomena, observed by a shift of resonance curve towards higher frequencies (indicating hardening) or towards lower frequencies (indicating softening). The nonlinear behavior may result from stretching, as thinner beams are more likely to be of dominant configuration. Consequently, to achieve a nonlinear device, we considered C-C beam to be thinner.

3.9 COMSOL simulation analysis (frequency tuning with DC excitation)

Frequency tuning of MEMS sensor allows for the coverage of broader frequency ranges within a single sensor beam and minimizes the number of sensors required to cover acoustic ranges. Therefore, in order to ascertain this, it is required to first simulate and study the behavior of sensor under various DC voltages, followed by testing it under a variety of scenarios. FEM simulations have been conducted using the COMSOL Multiphysics simulation tool. Various DC voltages ranging from 100 mV to 600 mV have been applied, and the corresponding resonance frequency shifts have been obtained. In addition, the temperature distribution (temperature dependence on the actuation voltage) and the sensor's displacement for the given voltages have been computed. The simulation outcomes at 600 mV DC are illustrated in the *Figure 3.6*. The resonant frequency shifts from 5.05 kHz to 6.17 kHz. The obtained temperature distribution with a maximum of 325 K results in a static deflection of 1.3 μm .

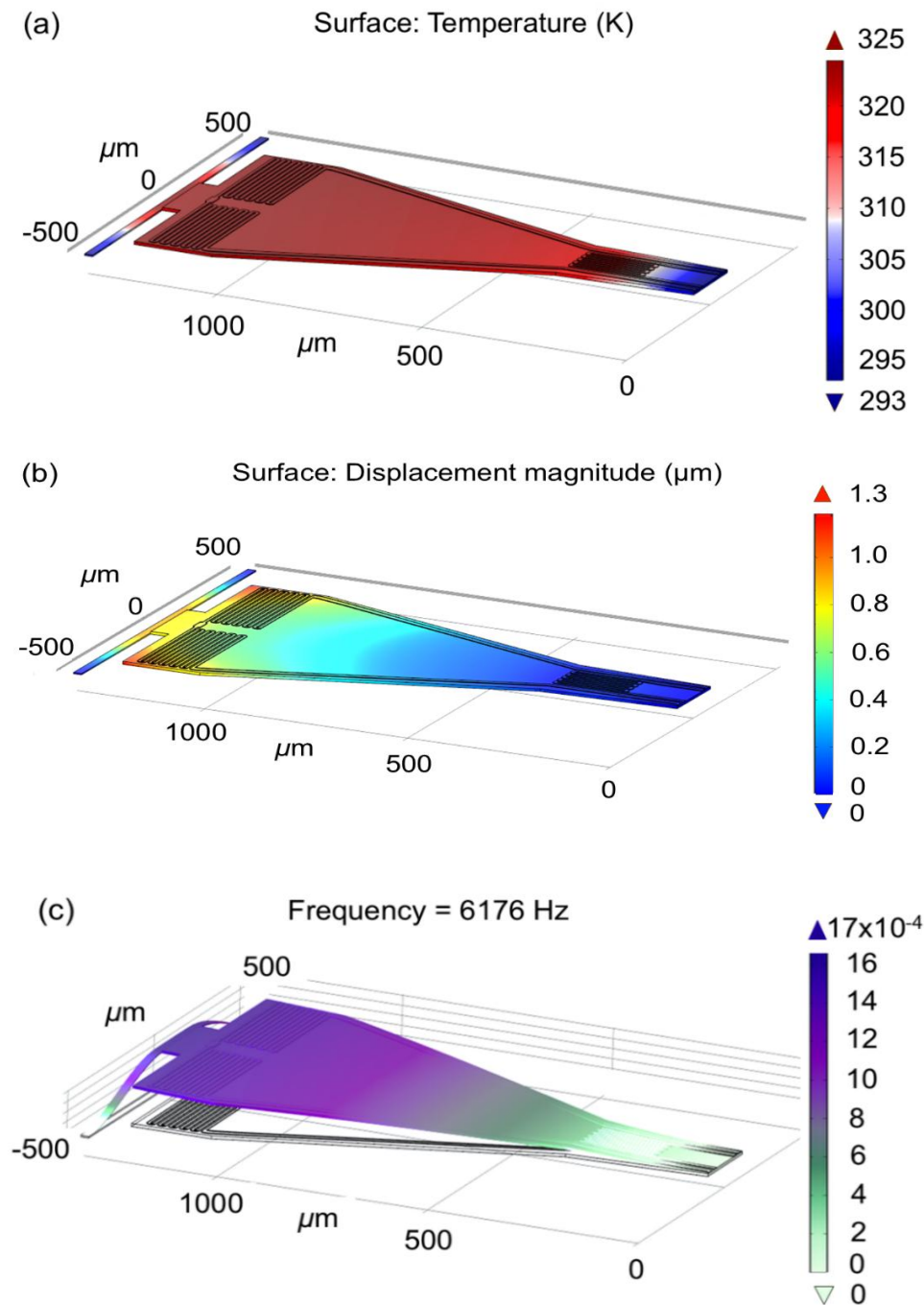


Figure 3.6 Finite element simulations of sensor 1 for an applied DC voltage of 600 mV: (a) temperature distribution, (b) static displacement of the sensor, and (c) mode shape for eigenfrequency analysis.

Given that the sensor is based on silicon and aluminium, we do not anticipate significant impact of thermal stresses on mechanical stability. However, temperature fluctuations can alter the dynamic behavior of sensor and affect resonance frequency. Nonetheless, this is a significant point, and control loops for retuning the sensor response can be engineered by modifying the DC voltages.

Furthermore, the influence/impact of aluminium (Al) layer thickness on the variation of resonance frequency has been investigated. The resonance frequency has been computed with and without accounting for the thickness of Al layer. The resonance frequency without the Al layer is 5.16 kHz, while the resonance frequency with the Al layer is 5.11 kHz (refer to *Figure 3.7*). This suggests that the Al layer has a minimal effect on the variation of resonance frequency.

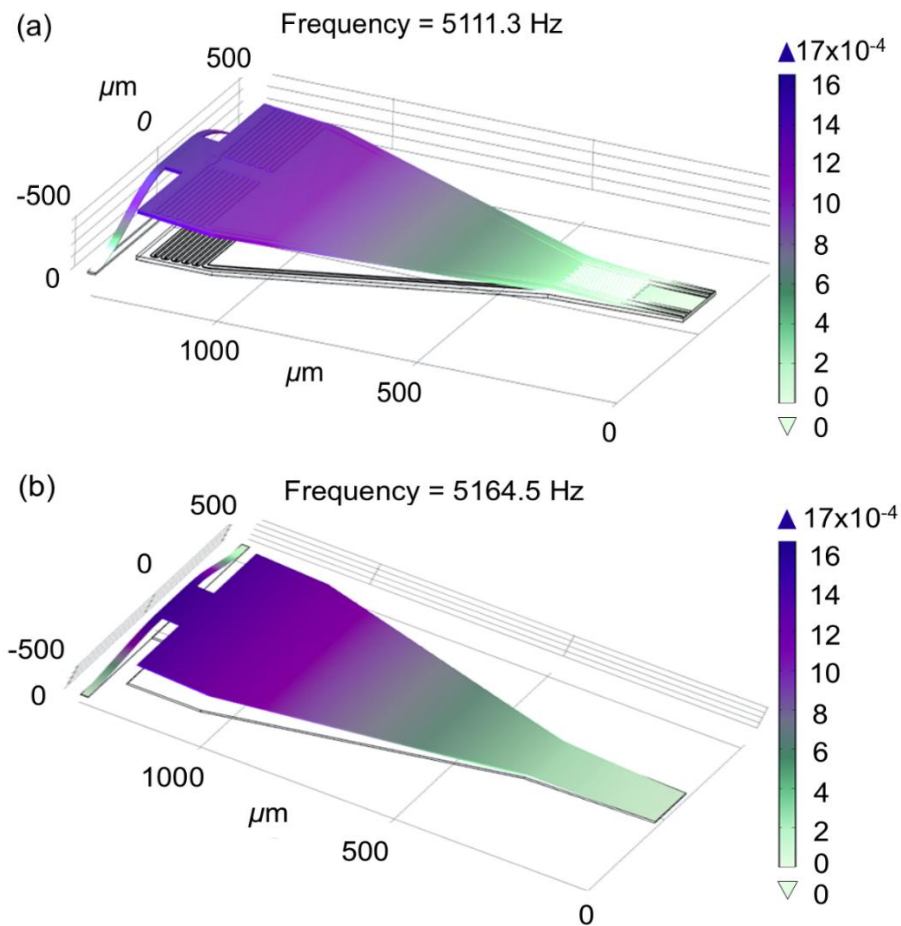


Figure 3.7 Effect of the thickness of Al layer on the change in resonance frequency: (a) without considering the thickness of the Al layer, and (b) with considering the thickness of Al layer.

Moreover, the response of sensor's temperature and displacement has been calculated when a DC voltage of up to 600 mV have been applied (see *Figure 3.8*). This analysis shows how the applied voltage causes a temperature increase in the sensor, resulting in mechanical displacement due to thermal expansion.

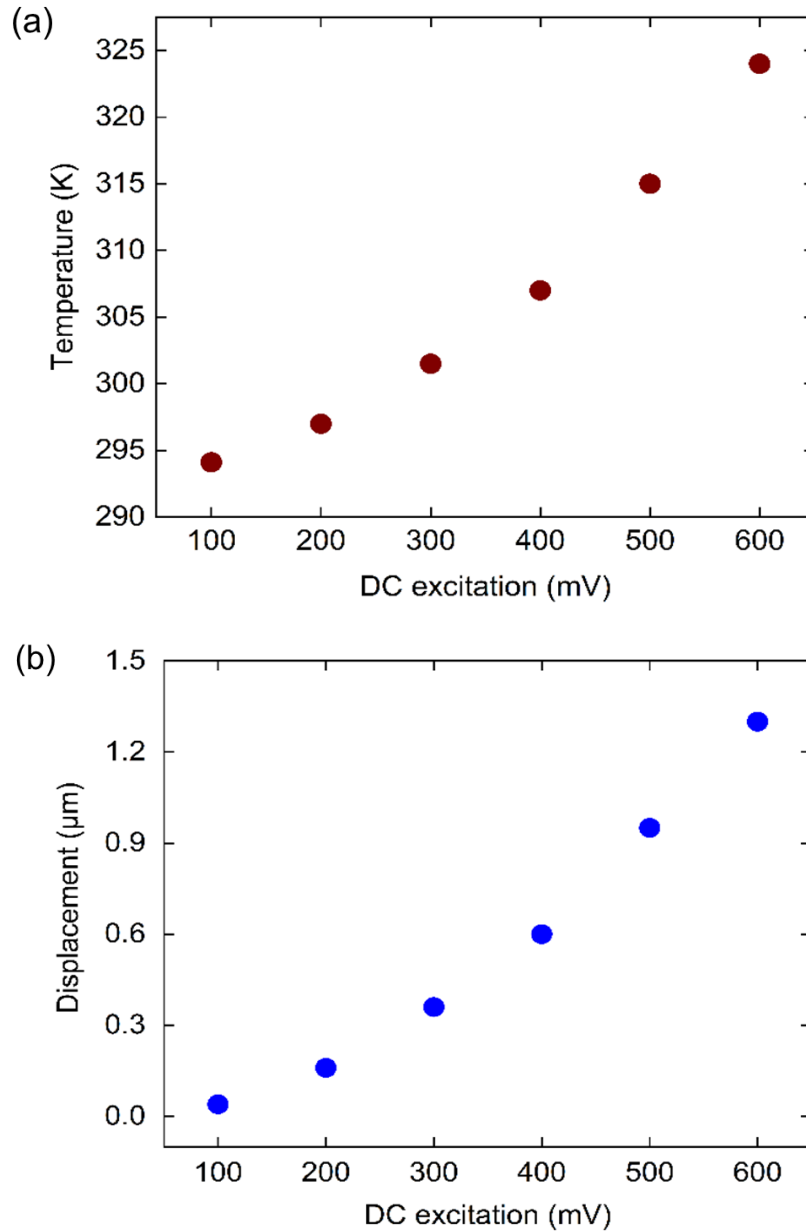


Figure 3.8 COMSOL multiphysics simulation analysis: (a) temperature variation in response to a DC voltage of up to 600 mV, and (b) COMSOL simulation analysis: cantilever displacement in response to a DC voltage of up to 600 mV.

3.10 MATLAB simulation

To better understand the behavior of sensor under a constant DC voltage, simulations have been performed in MATLAB using the sensor model shown in *Figure 3.9*. The harmonic balance method is used to approximate the steady-state solution of the nonlinear differential equation governing the sensor's mechanical response. This method assumes the solution is periodic and expresses it as a finite Fourier series, converting the problem into the frequency domain. In this analysis, sensor 1 (as listed

in Table 2.1) is used, based on its geometry and material properties. The simulation considers nonlinear behavior, where the stiffness of beam increases as displacement becomes larger. This is caused by geometric nonlinearity, which is included in the model through a cubic stiffness term. The simulation results provide several important insights for sensor design and fabrication: i) the model helps in determining how the sensor's resonance frequency changes with applied DC voltage, ii) avoiding undesired resonances by studying how the sensor responds across a range of frequencies, and iii) the vibration amplitude can influence beam thickness and material choices.

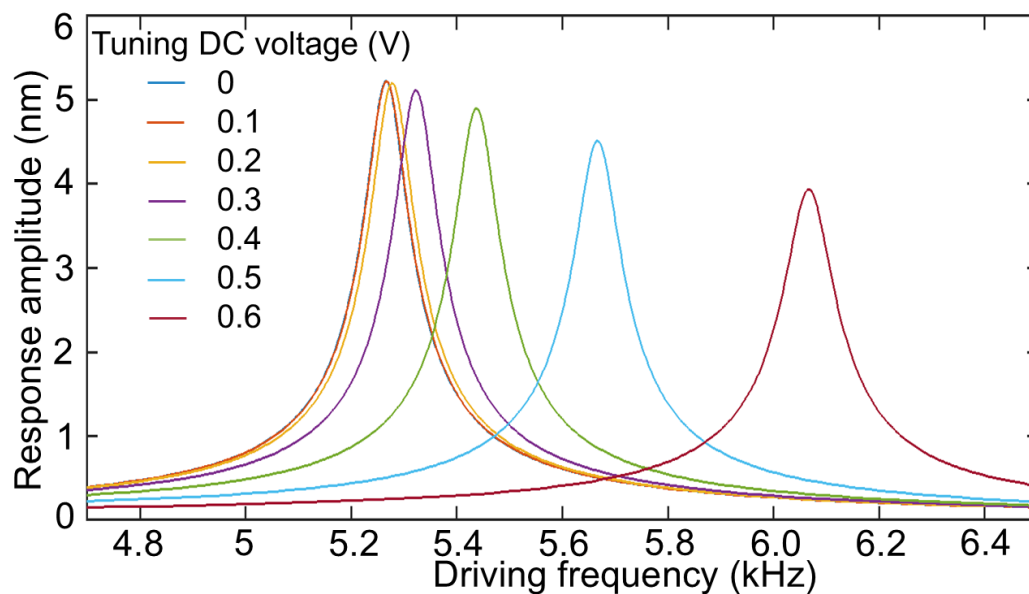


Figure 3.9 Simulation of the response amplitudes as function of the driving frequency for different DC voltages using the Harmonic Balance Method. The horizontal axis represents the driving frequency (in kHz), and the vertical axis shows the response amplitude of the sensor beam (in nm). The curve illustrates how the beam responds to a harmonic electrical excitation applied through a DC voltage source.

CHAPTER 4

DEVELOPMENT OF FREQUENCY TUNABLE BIO-INSPIRED ACOUSTIC MEMS SENSOR VIA GEOMETRIC NONLINEARITY

4.1 Need of frequency selectivity

Biological acoustic sensing with MEMS hair cells provides pre-processing capabilities, localized frequency-selective feedback, and dynamic adaptive features²³. Each sensor functions as a frequency filter. As a result, an array of sensors is necessary to cover the auditory range. To enhance the coverage of auditory range, we want to integrate frequency tuning for each sensor. Consequently, the development of bio-inspired acoustic MEMS sensors with adaptable frequency tuning capabilities is highly significant, as it enables coverage of broader frequency ranges within a single sensor beam and minimizes the number of sensors required to encompass acoustic ranges from 20 Hz to 20 kHz (refer *Figure 4.1*).

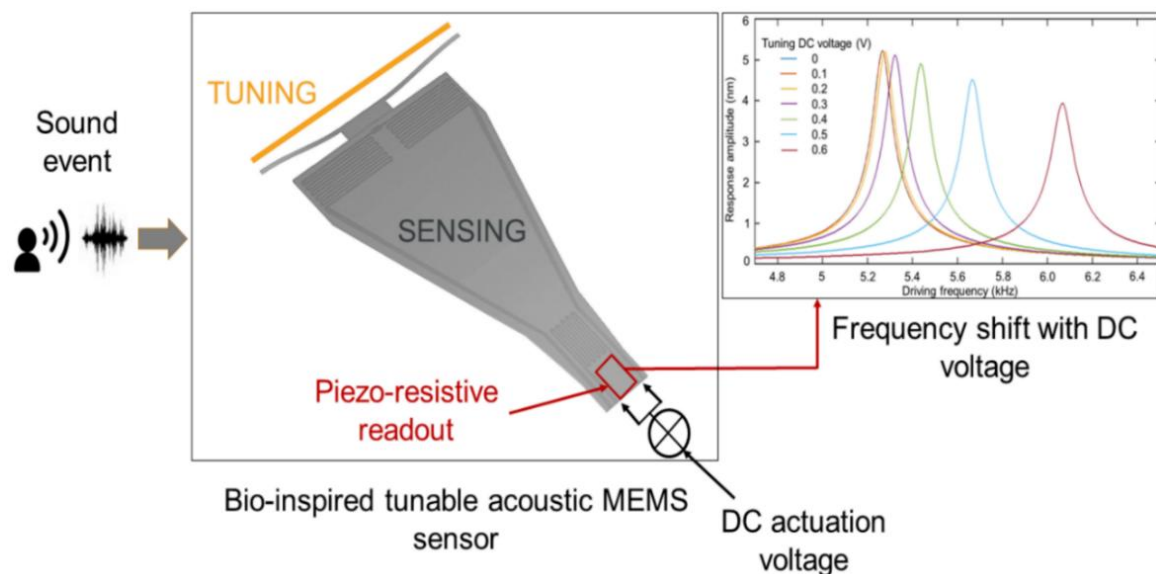


Figure 4.1 A Bio-inspired frequency tunable acoustic MEMS sensor comprising a sensing part, a tuning part, and a piezoresistive readout. A DC voltage of up to 600 mV was applied, resulting in a noticeable shift in the frequency shift.

With each part of the cochlea responds to a certain frequency range, and frequency decomposition of the cochlea refers to how the human ear separates incoming sound into different frequency components. To mimic the frequency decomposition function

of the human cochlea, the sensor system is designed to respond selectively to different frequency ranges. To integrate the frequency-decomposition of the cochlea in sensors, two methodologies are generally applied: (i) a single sensor (e.g., a membrane) of varying size and/or stiffness: thereby the resonance, i.e., the highest response amplitude for a certain frequency, occurs at distinct points of the membrane¹², which is normally sampled by electrodes at discrete membrane positions, and (ii) multiple sensors with various resonance frequencies. To sample a wider frequency range, an array of beams of various lengths and/or thicknesses is commonly utilized⁹⁰. Consequently, each beam is responsive to a small frequency range, resulting in a discrete sampling of frequencies. To cover a wide frequency range, a large number of sensors are required, as these sensors often have a high-quality factor, resulting in high sensitivity. In this work, methodology (i) is used: a single sensor with a resonance frequency that is dynamically tuned by varying the applied DC voltage. This methodology enables a single sensor to cover a broad spectrum of frequencies, thereby minimizing the need for many individual sensor elements while still achieving full frequency decomposition, similar to the cochlea.

4.2 MEMS sensor fabrication

The MEMS sensors have been fabricated using bulk and surface micromachining techniques⁵⁸. The fabrication steps of piezoresistive MEMS sensor beam are shown in *Figure 4.2 (a)*. A 4-inch n-type silicon wafer is used as the substrate material (1). A thermally grown layer of silicon dioxide (SiO_2) has been produced to ensure the electrical isolation (2). The following step involves a creation of heavily doped p++ connections by high dose boron implantation and thermal annealing to produce low ohmic connections to the piezoresistors (3). Next step involves the forming of piezoresistors by the consequent boron implantation (4). Then, employing plasma enhanced chemical vapor deposition (PECVD), SiO_x layer is deposited which serves as an electrical passivation layer (5). After that, contact pads are lithographically defined and wet chemical buffered oxide etching (BOE) etching is carried out (6). Furthermore, rather than contact type lithography MLA 150 Maskless Aligner exposure tool is used for lithography that offers non-contact exposure, flexible, ease of use, high speed and an excellent resolution. A 1 μm thin layer of Aluminium (Al) is then deposited using a magnetron sputtering technique (7). The material of one layer of a

bimorph cantilever is constraint by technological limitations in an actual system. In our particular instance, this is the silicon layer.

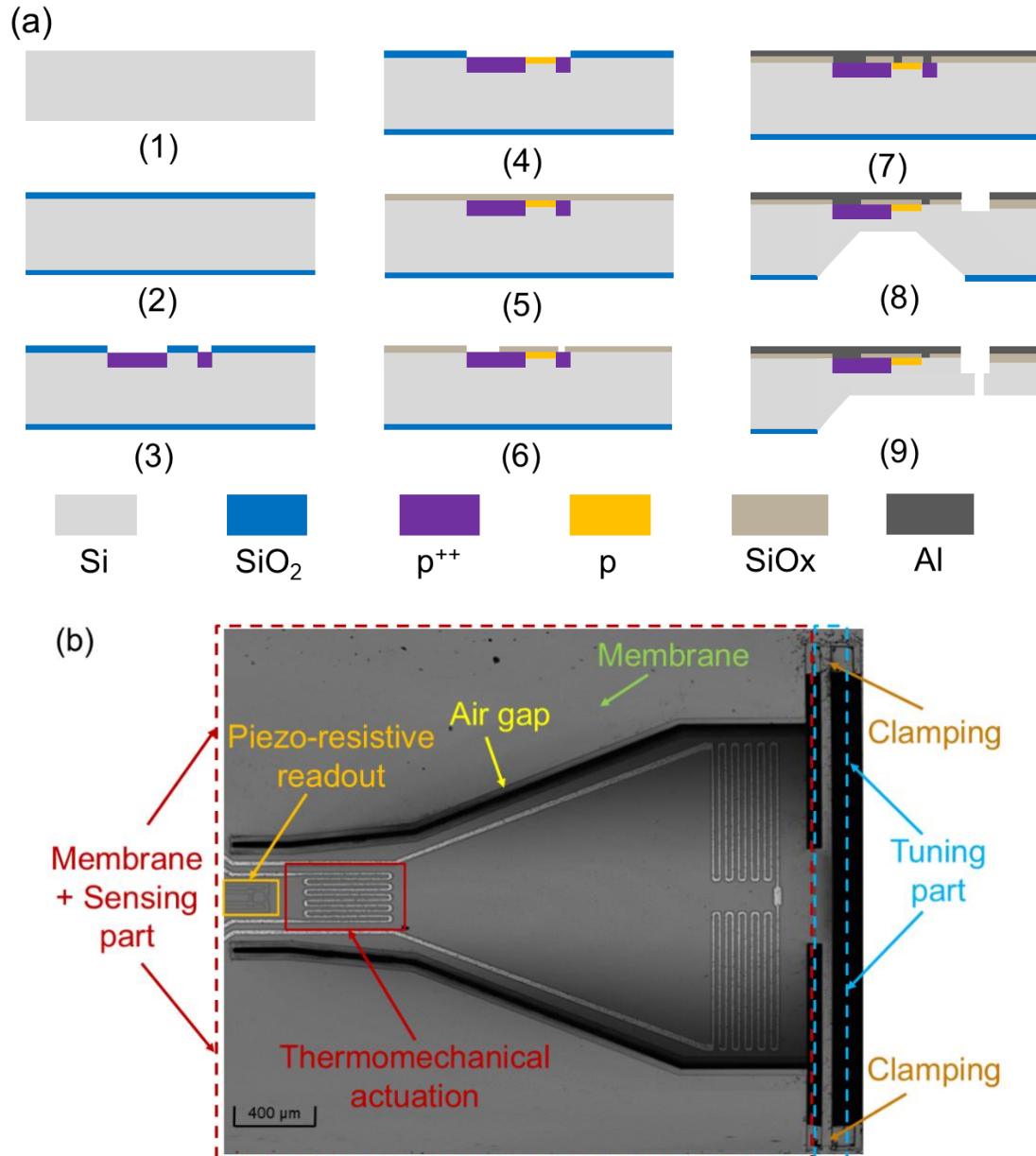


Figure 4.2 (a) Schematic representation of fabrication processes steps of MEMS sensor: (1) Selection of silicon substrate, (2) SiO₂ layer grown, (3) heavily doped p⁺⁺ connections by high concentration boron diffusion and thermal annealing, (4) piezoresistors created by boron implantation, (5) deposition of SiO_x layer, (6) lithography and BOE etching for defining contact pads, (7) Al layer deposition, (8) membrane area defined, and (9) microstructures released, and (b) microscopic image of the fabricated MEMS sensor.

The second material must be selected with a potentially different coefficient of thermal expansion from the first material. We have selected the materials with a higher coefficient of thermal expansion. Here, Al is one of the potential materials that could be selected, as it is also compatible with MEMS technology. The deposition of various material layers with different coefficients of thermal expansion induces a thermal stress gradient, resulting in bimorph effect. Then, membrane area is subsequently defined on the rear side of wafer using lithography followed by etching with potassium hydroxide (KOH) (8). To optimize the etch rate of KOH solution on the micro-structures of membrane region, we have maintained a KOH concentration of 40%. The photoresist is removed from the substrate. The KOH temperature is maintained at 60°C for one hour and etching is performed during the initial one hour. The actual etch rate is subsequently verified using a profilometer. An etch rate of 13.05 μm has been attained within the initial hour. A 290 μm thickness is etched for cumulative length of 22 hours. To keep tuning beam thinner than sensing beam, front-side lithography is performed first. After that, sulphur hexafluoride (SF₆) plasma is used to etch through silicon membrane. In addition, the form of tuning and sensing part was done by next lithography and then released with SF₆. The microstructures are finally produced once the photoresist is stripped away in oxygen plasma (9). *Figure 4.2 (b)* depicts the microscopic image of the fabricated MEMS sensor.

Moreover, a manual wire bonder HB05 (TPT Wire Bonder GmbH & Co KG, Germany) is used to bond individual samples to the PCB in order to assess their electrical performance. Wire bonding is essential when assembling the semiconductor devices/sensors, as it creates electrical interconnections between the PCBs and anchor pads of sensor. The selection of wire bonding length is important in achieving electrical and mechanical performance, since it has a direct impact on reliability and functionality of the sensor. With consideration of wire material, diameter, and mechanical and thermal demands of the devices, these parameters are of utmost essential to consider for different application scenarios⁹¹. *Figure 4.3* depicts the setup used for wire bonding of MEMS sensor using TPT HB05 wire bonder. Prior to bonding, the sensor is affixed to the PCB using an epoxy-based polymer (EPO-TEK 301/B4 optical adhesive) and subsequently heated at 60 °C for one hour to ensure optimal adherence. The bonding is conducted using aluminium thin film wires (Al) varying in diameter ranging from 17-75 μm .

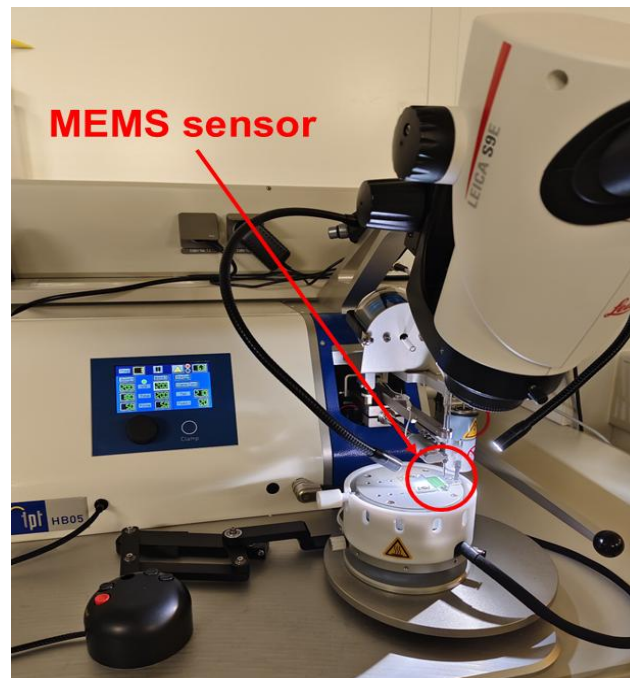


Figure 4.3 Setup for wire bonding of MEMS sensor using TPT HB05 wire bonder.

The wedge-wedge bonding method is employed in this instance. Wedge-wedge bonding is a solid-state wire bonding process that uses ultrasonic power and force to create bonds between the PCB and the anchor pads of the wafer. This bonding process allows for finer pitches ⁹¹. The bonding parameters, including bond temperature ($^{\circ}\text{C}$), bond time (ms), and bonding force (cN), have been optimized. The optimal bonding parameters are as follows: bonding force of 200 cN, bonding time duration of 50 ms, and temperature sustained at ambient conditions. One of the significant challenges observed during the optimization of wire bonding parameters are the partial damage to the bonding pads of silicon chips (see *Figure 4.4*).

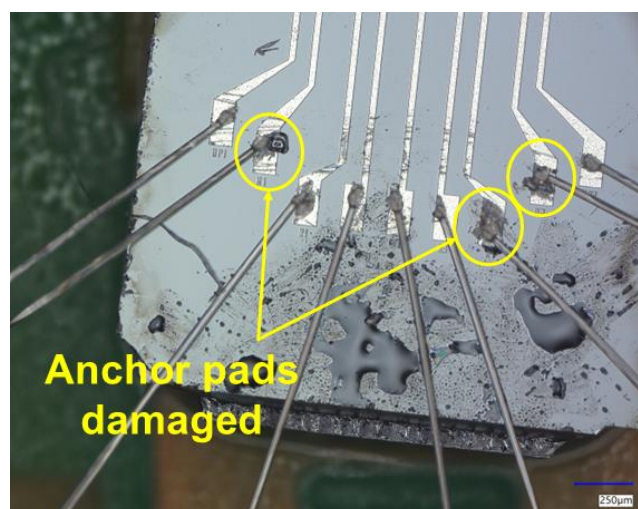


Figure 4.4 Challenges observed in wire bonding: anchor pads were damaged.

4.3 Measurement of resonance frequency using Laser Doppler Vibrometer (LDV)

The measurement of resonance frequency is accomplished through the use of Laser Doppler Vibrometer (LDV) (refer *Figure 4.5*). LDV is a measurement instrument that operates on the principle of Doppler effect. The Doppler effect is observed whenever the source of waves moves in relation to an observer. When there is a relative motion between the source and the observer, the frequency of a wave motion is altered as observed by the observer.

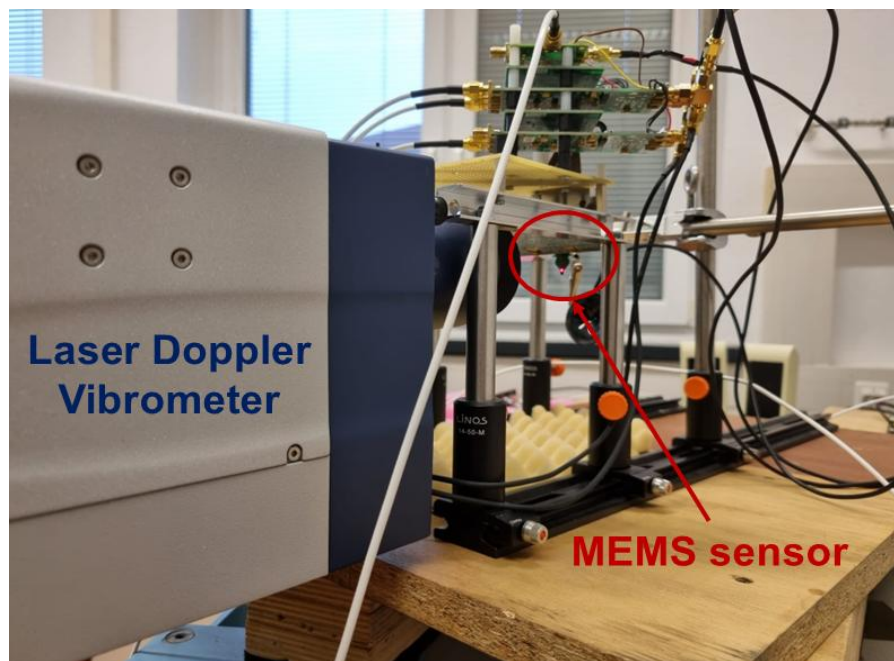


Figure 4.5 Setup for the characterization of a MEMS sensor using LDV.

The sensor dynamics have been assessed using LDV measurements, to verify the nonlinear behavior of the fabricated MEMS sensor. Initially, we tested the dependence of the pre-deflection upon DC power. This study aims to define the correlation between DC power and pre-deflection, as well as to ascertain the sensors bimorph efficiency. To better understand the sensor configuration and its operation, a schematic representation of the sensor is provided in Chapter 2. Additional information regarding the sensor design and working principles can be found in that chapter.

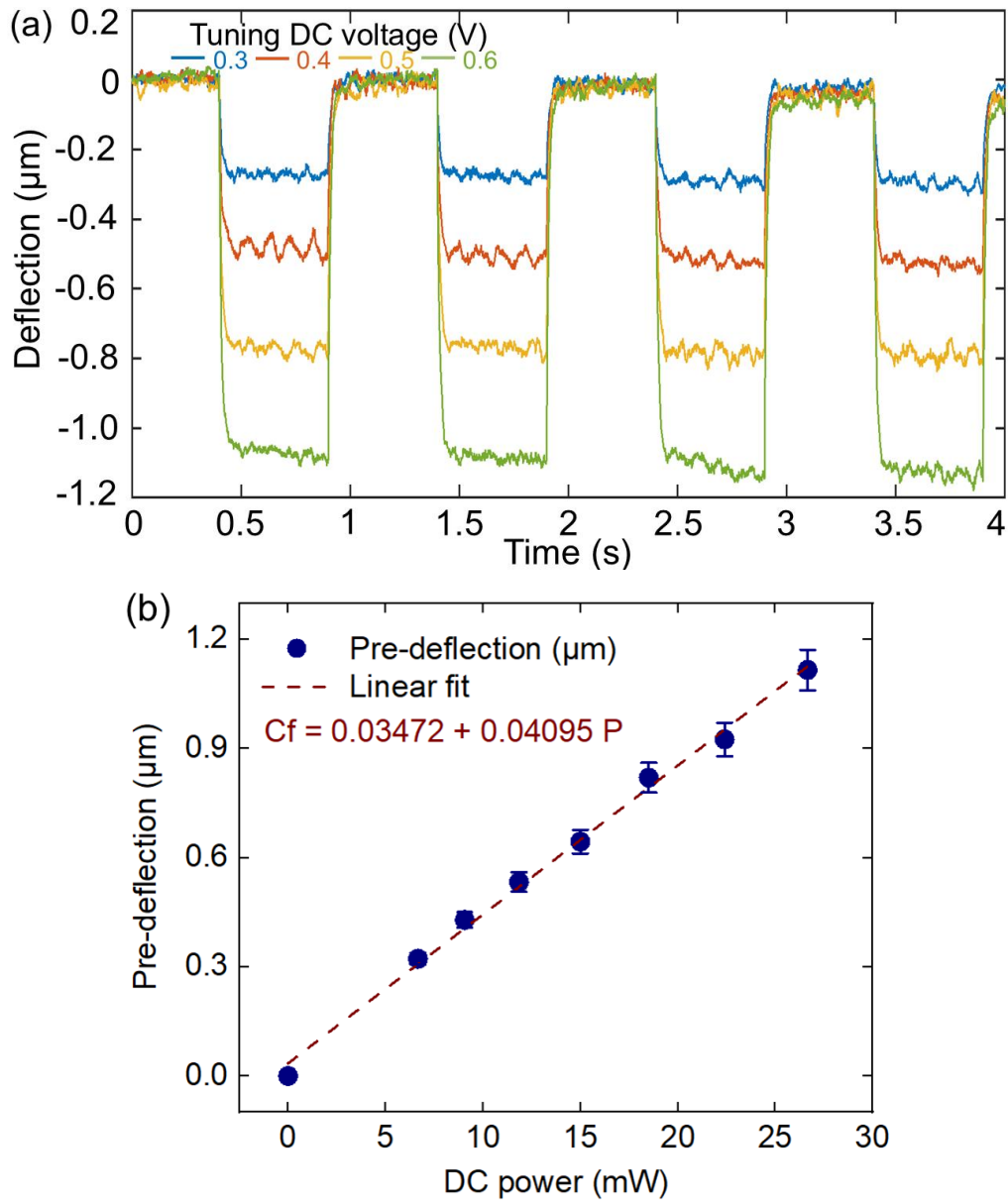


Figure 4.6 (a) DC dependence of pre-deflection evaluated for sensor 1: measured beam deflection for quasi-static actuation (1 Hz) for various DC voltages, and (b) extracted pre-deflection in dependence of DC power, used to obtain bimorph efficiency and working point z_0 .

The deflection of the free end of sensing part of the beam is measured for eight different actuation voltages when the beam is actuated with a slow varying signal of 1 Hz (quasi-static response) (refer Figure 4.6 (a)). The heat produced by the DC power deflect the micromechanical beam out of plane, which thus defines the pre-deflection of tuning part. Figure 4.6 (b) illustrates that the pre-deflections of sensor 1 range from 0 μm - 1.2 μm when DC powers of 0 mW - 28 mW are applied, respectively. Consequently, the DC power changes pre-deflection. To ascertain the working point

often denoted as z_0 , which refers to the deflection or displacement of actuator under applied actuation, and evaluate bimorph efficiency, it is essential to consider the actuation efficiency coefficients. Therefore, a linear fit has been used to fit the DC power versus the pre-deflection curve in *Figure 4.6 (b)* and the respective actuation coefficient C_f have been determined, The z_0 can be estimated by:

$$z_0 = C_f * P , \quad (4.1)$$

where, $P = \frac{U_{dc}^2}{R}$, U_{dc} is applied DC voltage (in mV), C_f is linear actuation efficiency coefficient, and R is resistance of the actuator (here: $R = 13.5\Omega$).

4.4 Electrical actuation measurement results

This section presents the measurement results in which the direct current (DC) voltage signals have been applied to the sensor, and resonance frequency changes has been measured. These findings help to better understand the sensor's response to different input voltages, particularly the extent to which the frequency shifts as a consequence of the input voltage. Each of the sub-sections below focuses on a different aspect of this response, starting with the spring hardening effect and then with the spring softening effect.

4.4.1 Spring hardening

Experimental tests have been conducted to ascertain the variation in resonance frequency with a small DC bias voltage, using electrical actuation. We applied different DC voltages while measuring the frequency response with the LDV. *Figure 4.7* shows the resonance frequency tuning with a small DC for three different sensors.

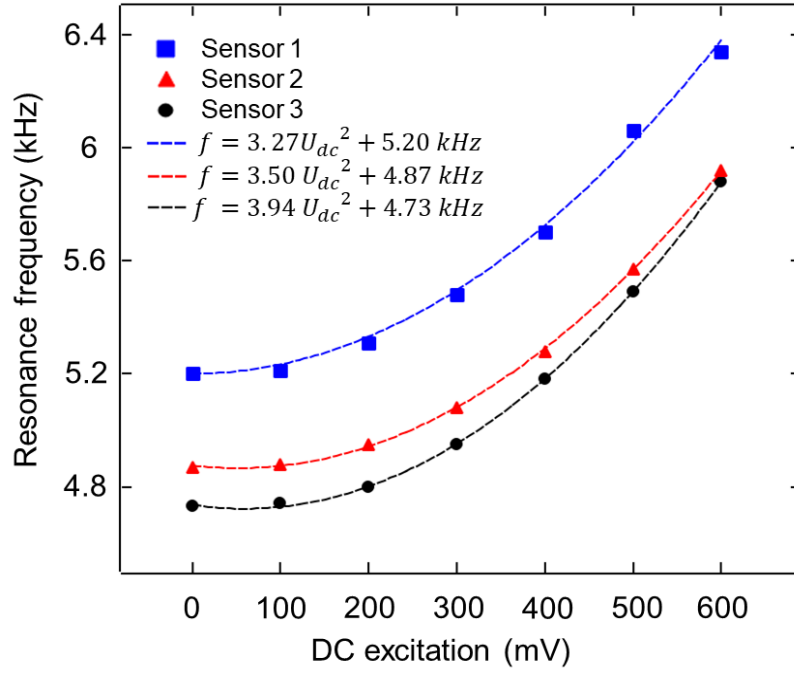


Figure 4.7 Dependence of resonance frequency on applied voltage analyzed for 3 sensors (electrical actuation): experimental results (symbols) and quadratic fit (dashed lines).

As observed, the resonance frequency increases from 5.20 kHz to 6.34 kHz for sensor 1, 4.87 kHz to 5.92 kHz for sensor 2, and 4.73 kHz to 5.88 kHz for sensor 3 as the applied voltage increases up to 600 mV. This behavior indicates the spring hardening behavior. In this case, the bimorph becomes stiffer with increasing actuation voltage, resulting in an increase in resonance frequency shift to higher values. Such spring hardening is typical in nonlinear systems and is primarily the result of geometric nonlinearities. As the bimorph bends more, internal stresses increase, making the structure stiffer.

4.4.2 Spring softening

In addition to spring hardening, we have also observed the spring softening behavior during the measurements for two different sensors. This occurs when the linear stiffness $k_1 > 0$, and nonlinear stiffness $k_3 < 0$ (The model has been previously described in Chapter 2, Section 2.3.3, with its formulation provided in Equation (2.14)). Nonlinear response is identified when the response curve shifts towards the reduced resonance frequencies. *Figure 4.8 (a)* shows that the resonance frequency for sensor 1 decreases from 5.8 kHz to 4.1 kHz, while for sensor 2 (*Figure 4.8 (b)*), it drops from 8.1 kHz to 7.3 kHz, as the DC voltage increases from 0 mV to 600 mV. This reduction

in resonance frequency indicates a spring softening effect. As the applied voltage increases, bimorph deflects more, which reduces the effective stiffness of the structure. Lower stiffness leads to a lower natural (resonant) frequency, which is typical of spring softening behavior in nonlinear systems.

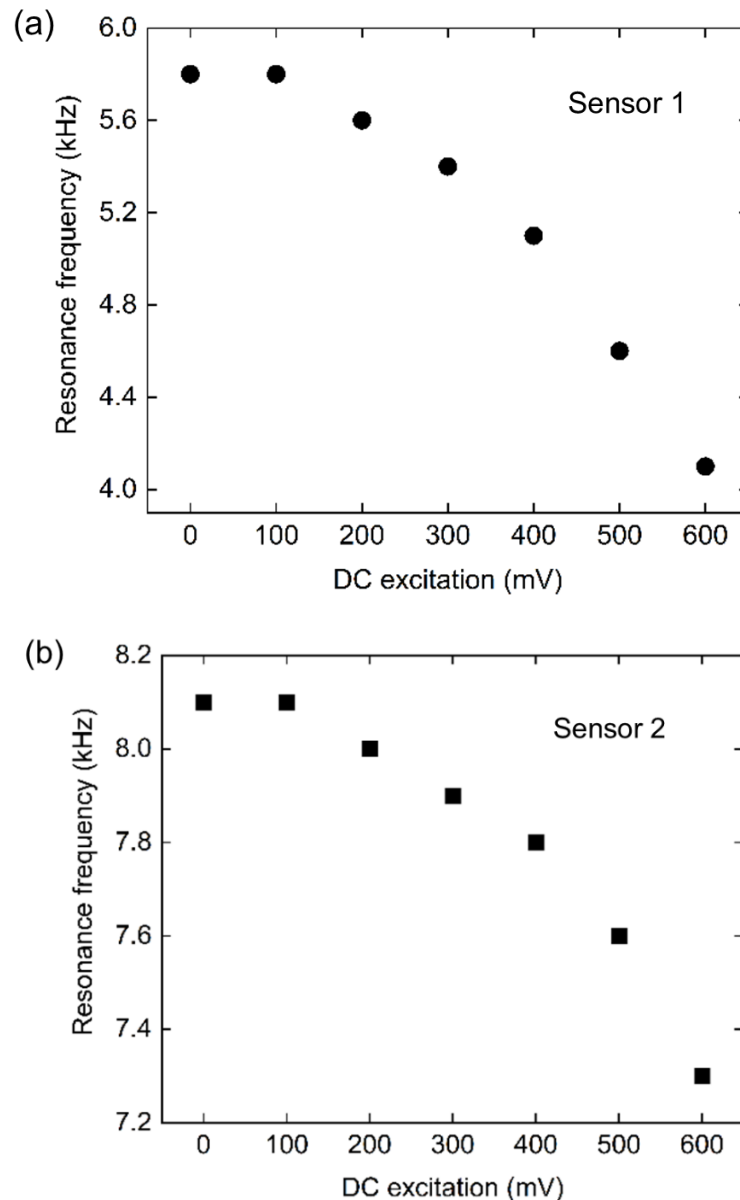


Figure 4.8 (a) and (b) shows the spring softening phenomenon seen in two distinct MEMS sensors when the DC voltage of up to 600 mV, respectively.

4.5 Quality factor (Q-factor) calculation

The quality factor, often known as the Q-factor, is a measure of how sharp or selective a resonance peak is. It reflects how well a resonant system store energy compared to how quickly it loses it. A higher Q-factor indicates that the system resonates more

strongly at a specific frequency and has a narrower bandwidth, making it is more selective to that frequency. In contrast, a lower Q-factor indicates that the system has stronger damping and can respond to a wider range of frequencies ^{92,93}. In this instance, the Q-factor is determined through experiments in which the sensor is actuated directly by the integrated bimorph actuator. For the actuation, a sinusoidal signal with a frequency sweep between 5.21 kHz to 6.34 kHz and an AC amplitude of 50 mV, and various DC voltages of up to 600 mV are applied. Thereafter, the amplitude response obtained from the LDV measurements have been fitted using Lorentzian function, and the quality factor is computed as $Q = \omega_{res}/\Delta\omega_{-3dB}$. This method is used due to the fact that resonance peaks in mechanical and electrical systems often follow a Lorentzian shape, especially near resonance. The frequencies at which the amplitude drops to $1/\sqrt{2}$ (approximately 70.7%) of the peak value are represented by -3 dB point. The -3 dB bandwidth provides a consistent and useful method for quantifying that sharpness ^{94,95}. *Figure 4.9* illustrates the measurement curve for the Q-factor calculation at 600 mV DC.

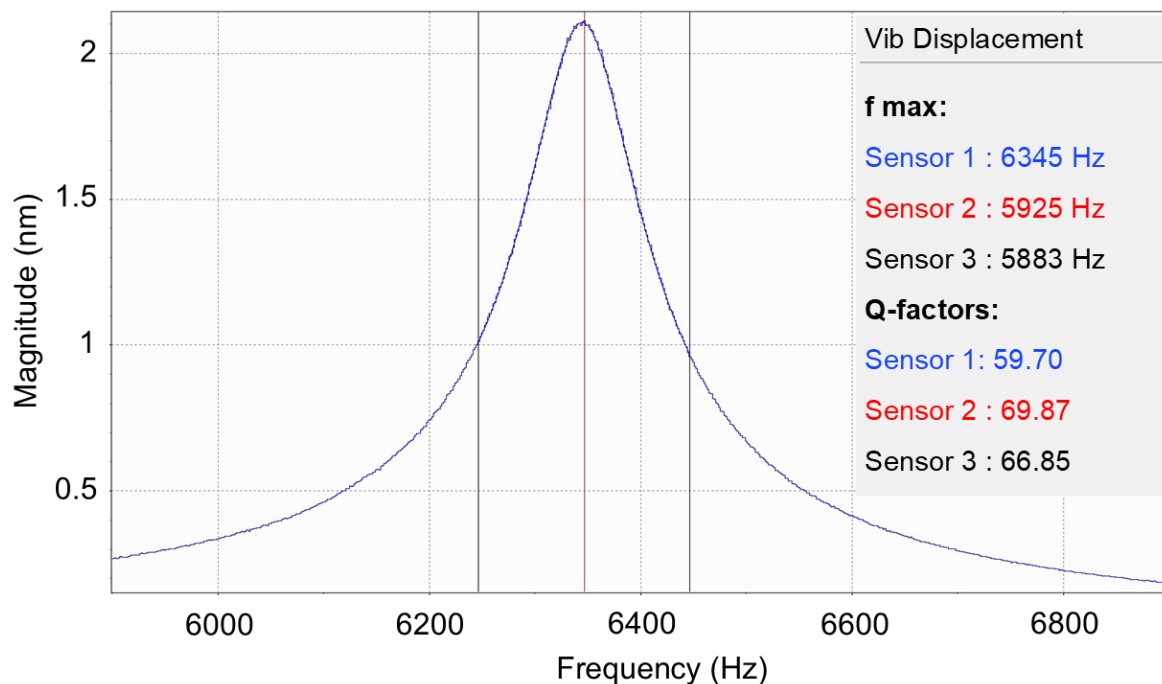


Figure 4.9 Measurement graph for the calculating the Q-factor. The inset table lists the measured frequencies and corresponding quality factors for three different sensors at 600 mV DC bias.

In addition, the square root dependence of the Q factor on frequency has been verified by analyzing the measured quality factor versus frequency by fitting (refer *Figure 4.10*).

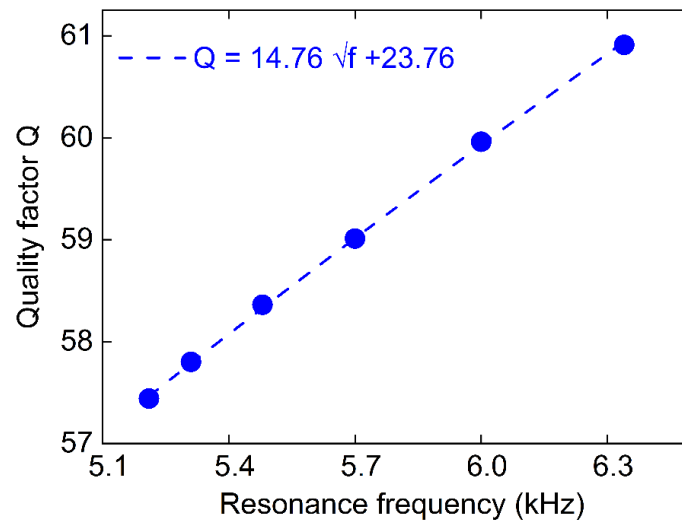


Figure 4.10 Square root dependence of the Q factor on frequency and frequency dependence of the quality factor.

4.6 Acoustic measurement results

To experimentally ascertain the resonance frequency change of acoustic response with a small DC bias, various DC voltages have been applied while measuring the frequency response to an acoustic signal using LDV. Consequently, different resonance frequencies have been measured for sensors 1-3 at various DC voltages (up to 600 mV). The results are illustrated in *Figure 4.11*. Using a quadratic fit, the dependence of resonance frequency on applied DC voltage can be obtained. A quadratic fit is used because, in MEMS structures, the variation in resonance frequency with voltage is nonlinear due to geometric effects. This quadratic behavior better represents linear and nonlinear components of the system's response than a simple linear fit. This dependence can be used to analyze the frequency components of an input sound signal while sensing, by sweeping applied DC voltage and detecting maxima in amplitude.

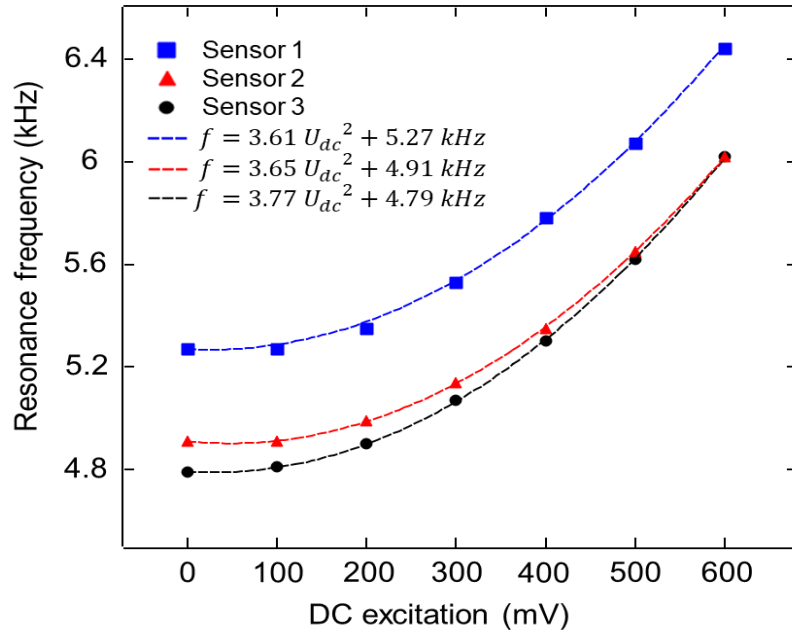


Figure 4.11 Dependence of resonance frequency on applied voltage analyzed for 3 sensors (acoustic response): experimental results (symbols) and quadratic fit (dashed lines).

Consequently, three sensors from a wafer, representing the manufacturing tolerances, are compared with natural resonance frequencies ranging from 4-6 kHz. Despite the fact that, three sensors exhibit same nonlinear behavior when DC bias voltages are swept up to 600 mV, a variation in their resonance frequencies are observed, visible as an offset between the three curves shown in *Figure 4.11*. This variation arises from the variability in thickness due to fabrication tolerances. Nevertheless, the resonance frequency of these sensors can be tuned to a proper working point by DC bias voltage. Consequently, compensating those unavoidable technology tolerances by adjusting the working point is an advantage of the presented design. From an application perspective, we can tune the sensors during operation by modifying the DC voltages.

The acoustic measurement of the response amplitudes as function of driving frequency for different DC voltages for sensor 1 are illustrated in *Figure 4.12*. These measurements show how the frequency and amplitude change with increasing voltage, highlighting clear shifts in both parameters. The resonance frequency shifts from 5.27 kHz to 6.14 kHz during measurements, while it shifts from 5.05 kHz to 6.16 kHz during simulation when the DC voltage is increased up to 600 mV.

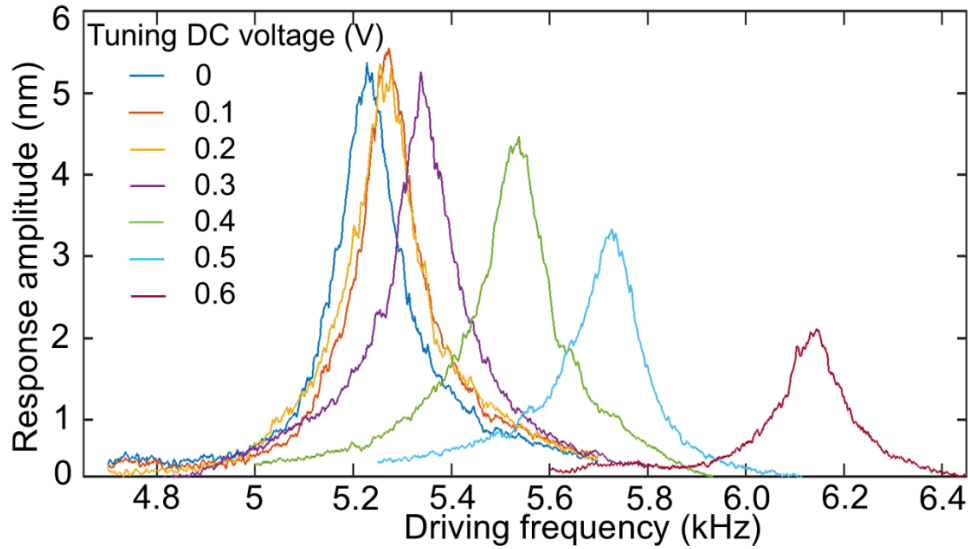


Figure 4.12 Acoustic measurement of the response amplitudes as function of the driving frequency for different DC voltages.

Moreover, the LDV scan showing the acoustically excited resonance mode of sensor 1 with a DC voltage of 600 mV applied has been shown in *Figure 4.13*. This result is important, as it clearly demonstrates how the sensor moves at resonance when excited by sound.

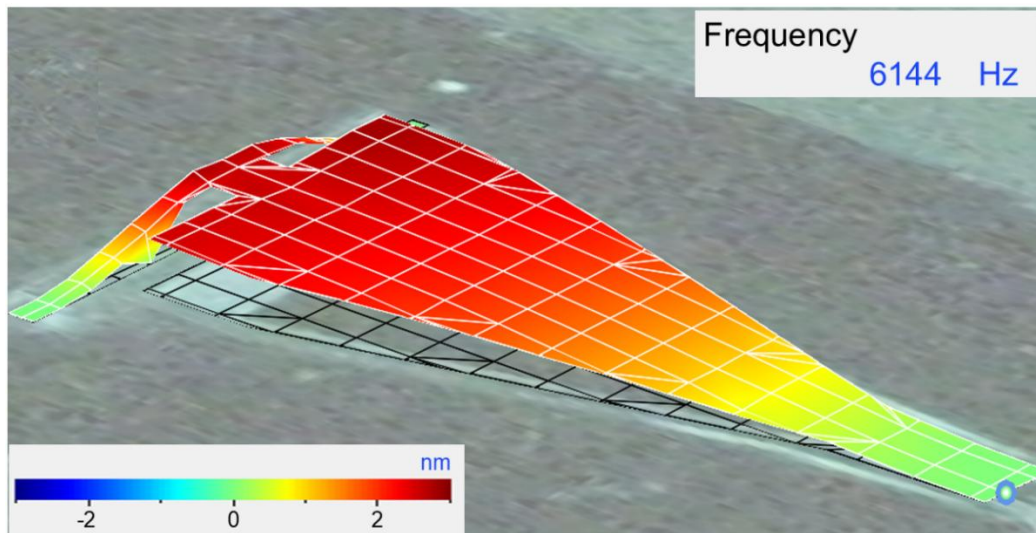


Figure 4.13 LDV scan of the acoustically excited resonance mode of sensor 1 with an applied DC voltage of 600 mV.

The resistance characteristics of the sensor in response to DC excitation have also been studied. *Figure 4.14* shows that the resistance changes from 13.8 Ω to 14.5 Ω when the DC voltage increases to 600 mV. A gradual increase in resistance may result from various factors such as Joule heating, and fluctuations in contact resistance.

Joule heating can affect the material characteristics and cause thermal drift, lowering accuracy and sensitivity⁵⁶. Moreover, the fluctuations in contact resistance can cause signal instability and noise, hence lowering sensitivity and reliability⁹⁶. Thus, monitoring these effects is therefore necessary to ensure the sensor's accuracy and stability over time⁹⁷. *Figure 4.14* illustrates the variation in resistance as a function of DC voltages for the presented sensor 1.

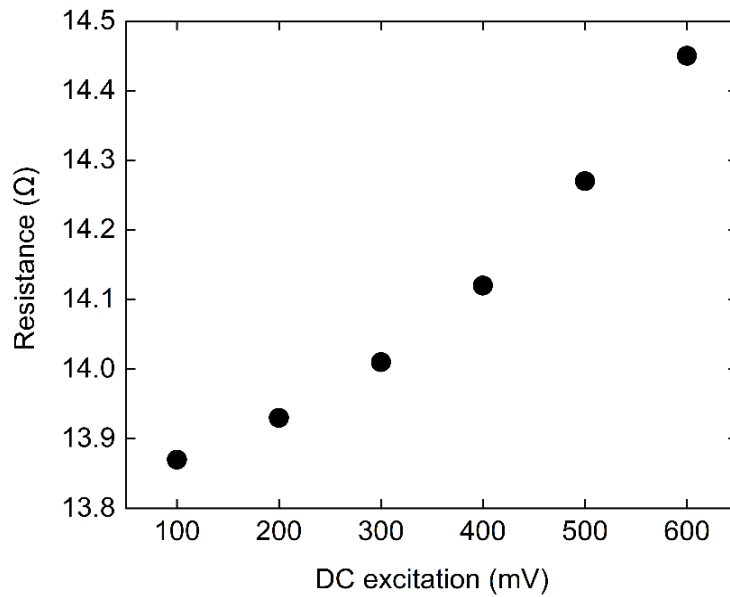


Figure 4.14 Variation in resistance observed when the DC voltage is swept up to 600 mV.

4.7 Comparison of acoustic measurement and simulation results

Lastly, to validate our model, a comparison has been made between the simulation results, which are computed and subsequently utilized for the description of experimental findings. The model is described in detail in Chapter 2, Section 2.3.3. *Figure 4.15* illustrates the comparison between the calculated and experimentally obtained resonance frequency change resulting from DC excitation. A resonance frequency shift of approximately 1.20 kHz is achieved for DC excitations up to 600 mV. Thus, the dependence of resonance frequency on DC excitation, as observed in experiments, can be effectively described by Duffing-based oscillator model presented above. However, the differences between simulation and experimental results may be due to variety of factors, including model simplifications, fabrication variabilities (may result in variations in sensor properties, mainly frequency, and systems properties can be limited by technological constraints).

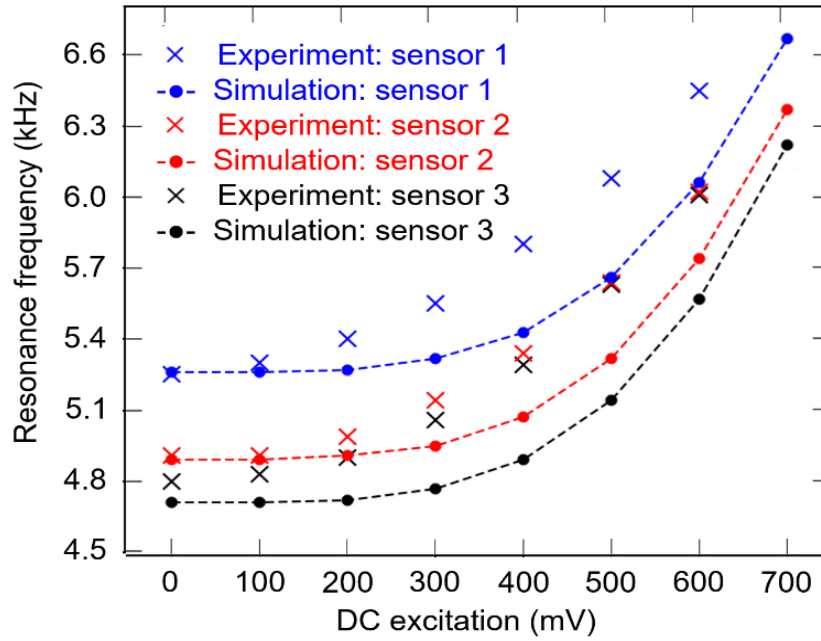


Figure 4.15 Comparison of experimental findings (crosses) with modelling results (dashed line) for 3 different sensors: resonance frequency extracted from acoustic response for different applied DC voltages up to 700 mV.

4.8 Application of frequency tuning for frequency analysis of sound input

Beside static tuning of the applied DC voltage, used in previous section to set the operation point, we can tune the sensors while in operation by dynamically changing the DC voltages. From Figure 4.11, the dependence of resonance frequency on applied DC voltage can be obtained using a quadratic fit. This dependence can be used to analyze the frequency components of an input sound signal during sensing by sweeping the applied DC voltage and detecting the maxima in amplitude.

To demonstrate this, we apply a sound signal to the sensor, which consists of four tones with similar amplitude, namely at 5500 Hz, 5800 Hz, 6000 Hz and 6200 Hz. Then, the applied DC voltage is swept from 0 mV to 600 mV, as shown in Figure 4.16 (a). The corresponding resonance frequency is calculated from the quadratic fit $f = 3.61 U_{dc}^2 + 5.27 \text{ kHz}$ for sensor 1 in Figure 4.11. The output of sensor is the voltage signal obtained from the Wheatstone bridge, shown in Figure 4.16 (b). The response of sensor clearly shows the resonance at four tones as increasing amplitude above the noise level (marked by ellipses in Figure 4.16 (b)). Since the DC values for each time instant is known, the frequency of the tones can be directly determined from the time point of the resonances (maxima in sensor signal). The time-dependent shift of

resonances is furthermore visible from a spectrogram plot of sensor signal (see *Figure 4.16 (c)*).

The shift over time of the four resonances are visible, which occur due to the change in DC voltage. Note DC changes here linearly from 0 mV to 700 mV until 5.2 s and then from 700 mV to 0 mV until 10 s. Thus, by incorporating a peak detection routine and conversion of the DC value into the resonance frequency, the sweep of the applied DC voltage can be used to extract the frequency components of the sound signal, i.e. the four tones. In this way, frequency decomposition in hardware is possible using the sensor directly, without the need to implement a Fourier analysis or a filter bank.

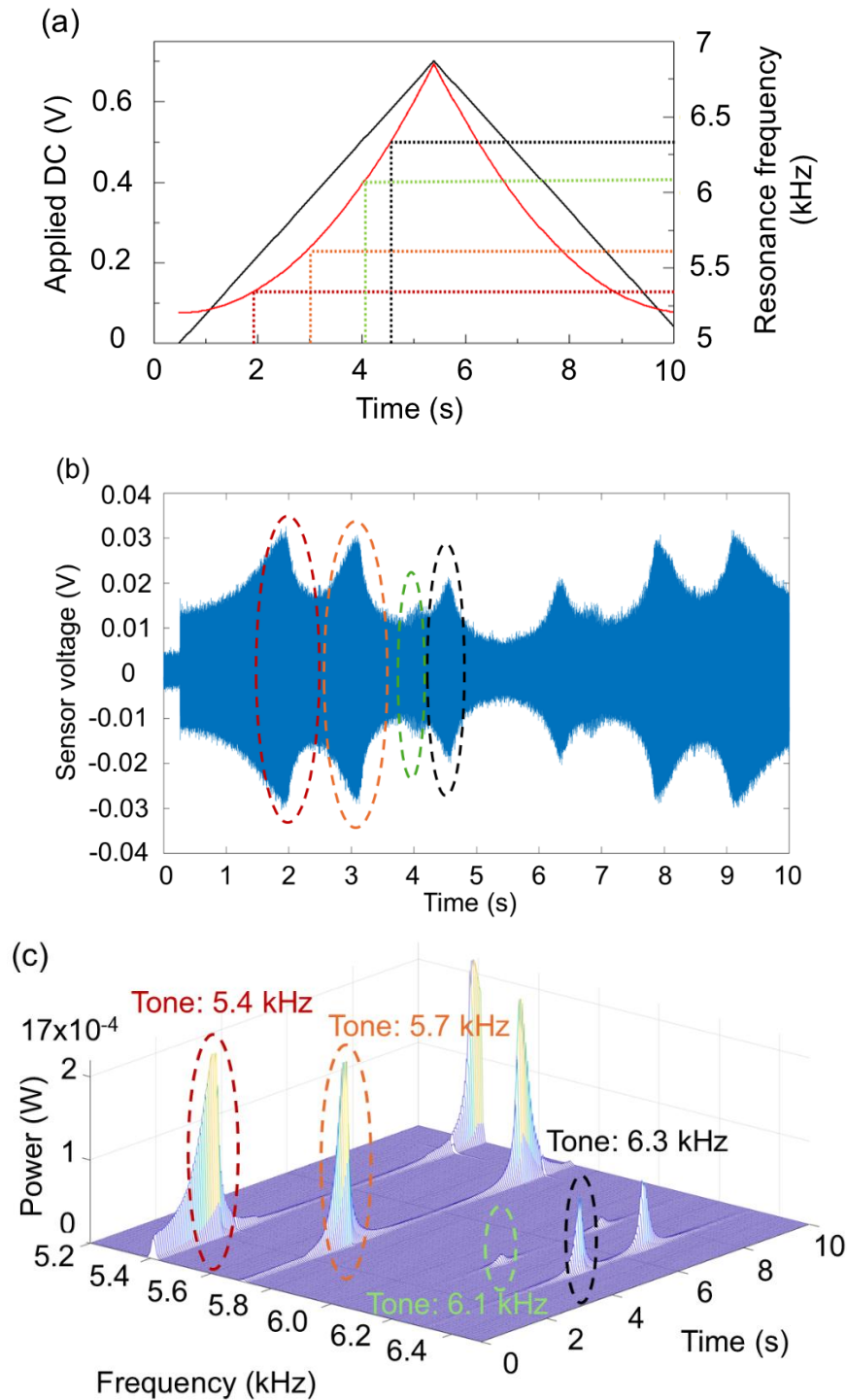


Figure 4.16 Analysis of sound frequencies with sensor 1: (a) applied DC voltage over time and corresponding, calculated resonance frequency of the sensor over time. (b) sensor signal, i.e. voltage of Wheatstone bridge after amplification and high-pass filtering, over time in response to a constant sound with four tones. Clearly, the four different resonances are visible. (c) spectrogram of sensor signal for sweep of DC voltage from 0-700 mV (0-5.2 s) and 700-0 mV (5.2-10 s). All four tones of the sound signal are detected.

CHAPTER 5

DEVELOPMENT OF FREQUENCY TUNABLE MEMS SENSOR FUNCTIONALIZED BY NI-TI SHAPE MEMORY ALLOY

5.1 Introduction and Motivation

This chapter presents the development of an intelligent MEMS sensor with tunable frequency. Unlike conventional MEMS sensors, which only detect current states, and responding to an external stimuli such as temperature, intelligent sensors are designed to go further. They are capable of sensing, storing, and interpreting information. This is made possible by combining sensing, actuation, and memory components into a single system, all connected through a feedback loop⁹⁸ (see *Figure 5.1*). This integration allows the sensor to not only respond, but also recognize patterns, store them as knowledge, and adapt its behavior over time. To realize this, the sensor design incorporates a special class of smart materials known as shape memory alloys (SMAs).

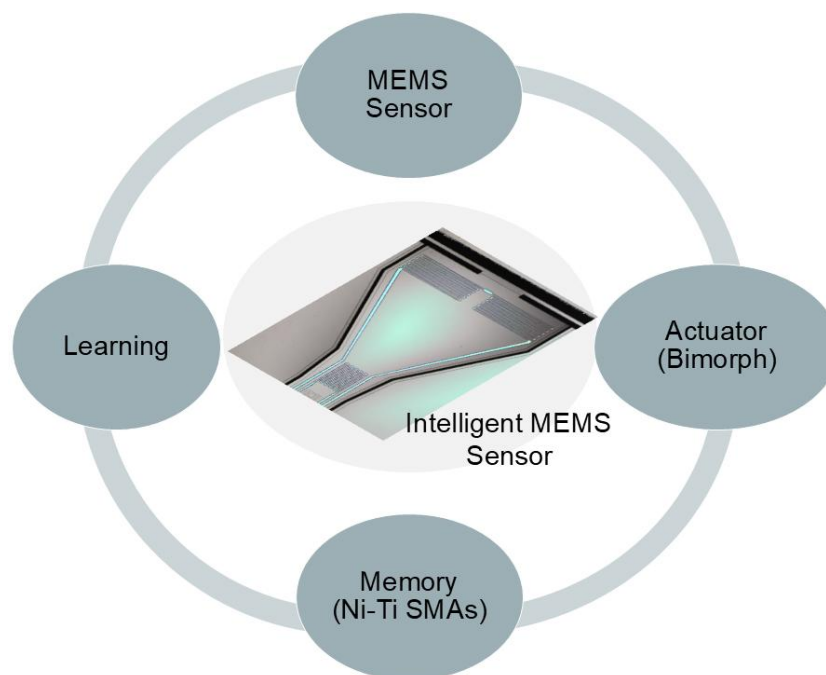


Figure 5.1 Integration of MEMS sensor, actuator (bimorph), and memory (Ni-Ti SMAs) forms an intelligent MEMS sensor.

SMAs are intermetallic compounds capable of memorizing a predefined shape and exhibiting shape recovery during thermal cycling⁹⁹. This unique behavior is due to

reversible phase transformation between two crystal structures: martensite at low temperatures and austenite at high temperatures. Because of this property, SMAs can respond to temperature changes by altering their shape, or stiffness, making them ideal for combining sensing and memory functions within a single material ¹⁰⁰. The development of MEMS-based sensors and actuators using SMA thin films has increased significantly in recent years ^{101–103}. SMAs are in high demand in a variety of applications, including medical/biomedical ^{104–106}, energy harvesting ¹⁰⁷, aerospace ¹⁰⁸, automobiles ^{107–109}, and MEMS-based sensors ^{110–113}, and actuators ^{114–116} driving continued development in this field. Among the various categories of smart materials reported in the literature, sputter-deposited nickel-titanium (Ni-Ti) shape memory alloys are considered highly promising for MEMS applications due to their distinctive properties. These include superelasticity ¹¹⁷, which allows large, reversible deformation, shape memory effect (SME) ¹¹⁸, which enables the material to recover its original shape after deformation, high energy density ¹¹², and the ability to undergo large recoverable strains ¹¹⁹. Incorporating SMA inside the MEMS sensor allows the material to store information and contribute to the sensor's adaptive behavior. The integration of Ni-Ti SMA makes it possible to create an intelligent sensor that can learn, store information and adapt over time.

5.2 Phenomenon of shape memory effect

The ability of a material to remember and return to a predetermined shape upon exposure to a specific external stimulus i.e., thermal cycle is known as shape memory effect (SME). This phenomenon is the result of thermally induced crystallographic phase transformations within the material. The shape memory-related phenomenon was first reported in the 1930s through studies on Au-Cd and Cu-Zn alloys, where reversible deformation and temperature-dependent phase transformations were observed ^{120, 121}. However, the phenomenon gained wider recognition after Buehler et al. demonstrated the shape memory effect in near-equiatomic Ni-Ti compositions in 1963 ¹²². This material, later named Nitinol, marked the beginning of its development for real-world applications due to its remarkable ability to recover its original shape upon heating, enabling a wide range of technological applications. There are two types of SMEs: one-way shape memory effect (OWSME), and two-way shape memory effect (TWSME) ¹²³. *Figures 5.2 (a), and 5.2 (b)* illustrate the process chains for one-way,

and two-way shape memory effects, respectively. In this dissertation, one-way shape memory effect has been the primary focus of investigation.

5.2.1 One-way shape memory effect (OWSME)

OWSME refers to the ability of a material to retain only its parent phase form. In this, shape memory material remembers its original shape when heated above its transformation temperature (into the austenite phase), and can be deformed at lower temperatures (into the martensite phase) (see *Figure 5.2 (a)*). The development of OWSME involves a specific training process, which consists of: i) the material is plastically deformed in its low-temperature martensitic state, ii) upon heating, it transforms into the austenitic phase, and recovers its original, pre-deformed shape, and iii) when cooled back to the martensitic phase, the shape remains unchanged unless the material is manually deformed again. OWSME is used in a wide range of applications, including medical devices (stents, dental braces, orthopedic implants, surgical tools), actuators, grippers, drug delivery systems and so on ^{124–126}.

5.2.2 Two-way shape memory effect (TWSME)

In TWSME, a material can transition between two distinct configurations during thermal cycling, one upon heating (austenitic phase) and another upon cooling (martensitic phase) without requiring manual deformation (see *Figure 5.2 (b)*). Unlike the one-way effect, TWSME enable reversible shape changes purely through temperature variation, with no external mechanical stress applied during the cycle. The development of TWSME involves a specific training process, which consists of repeated thermal and mechanical cycling to induce the two-way effect ^{127,128}. After training, the material remembers one shape in the martensitic phase (cooling) and a different shape in the austenitic phase (heating), enabling reversible switching between the two configurations with each thermal cycle.

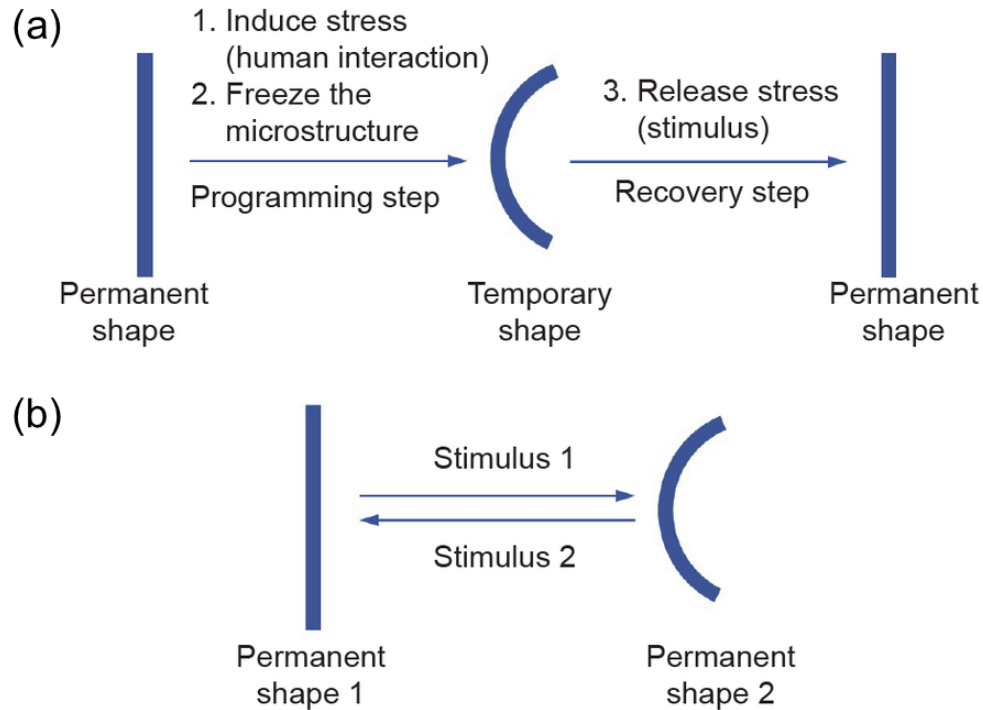


Figure 5.2 Schematics of process chain for: (a) one-way shape memory effect, and (b) two-way shape memory effect (adapted from ¹²⁹).

In this case, the material transitions between two distinct shapes independently as the temperature changes. This effect totally depends on the microstructural changes that are influenced by internal stresses generated during phase transitions ¹³⁰. TWSME is applicable to a wide range of applications, including advanced robotics, morphing aerospace components, self-adjusting devices and so on ¹³¹.

5.3 Phase transformations in shape memory alloys

Shape memory alloys undergo a solid-state phase transformation that begins at one temperature and completes at another, depending on whether the material is being heated or cooled. These temperatures, called as transformation temperatures, indicate when the material changes from its high-temperature phase (austenite) to its low-temperature phase (martensite), and vice versa. It is the underlying physical effect which defines temperatures. Therefore, identifying these transformation temperatures are essential for understanding and utilizing the shape memory behavior. The shape memory behavior is observed during the phase transformations between the two distinct crystallographic phases namely:

i) Austenite: the high-temperature phase with a high degree of symmetry, typically in the form of simple cubic crystal structure. When the material is heated above its transformation temperature, it transitions into austenite phase. The supplied heat energy facilitates the atomic rearrangement, allowing the material to return to its original shape. In this phase, the material is in its most stable (lowest energy state) form and can take only crystalline structure ¹³².

ii) Martensite: the low-temperature phase with a low degree of symmetry, typically in the form of tetragonal, orthorhombic, hexagonal, or monoclinic structures ¹³³. The martensitic transformation is a lattice distortion as well as structural transformation process, that involves the rearrangement of austenite atomic crystals into martensite atomic crystals. This is caused by the application of stress, which is mostly dependent on the composition of Ni-Ti alloy and the thermal conditions. In the martensite phase, the material is more easily deformed and can take any number of crystalline forms ¹³⁴.

These austenitic and martensitic transformations are temperature-dependent, and specific temperatures defines the start and end points of each phase during both heating and cooling cycles. These include: i) martensitic finish (M_f) refers to the temperature at which transformation to fully twinned martensite is complete during cooling, without any further shape change upon unloading, ii) martensitic start (M_s) refers to the temperature at which the austenite phase begins to transform into martensite upon cooling, iii) austenitic start (A_s) refers to the temperature at which the martensite begins to transform into austenite upon heating, and iv) austenitic finish (A_f) refers to the temperature at which the transformation to fully austenitic structure is complete. During cooling, the phase transformation starts at M_s , and completes at M_f , while during heating, transformation begins at A_s and finishes at A_f respectively. The transformation occurs during heating is typically referred to as reverse transformation, while the transformation occurs during cooling is typically referred to as forward transformation ¹³⁵. The thermomechanical behavior, composition and applied stress all play critical roles in influencing the properties of Ni-Ti SMAs ^{119,136,137}. *Figure 5.3* illustrates the temperature-induced phase transformation in Ni-Ti SMAs.

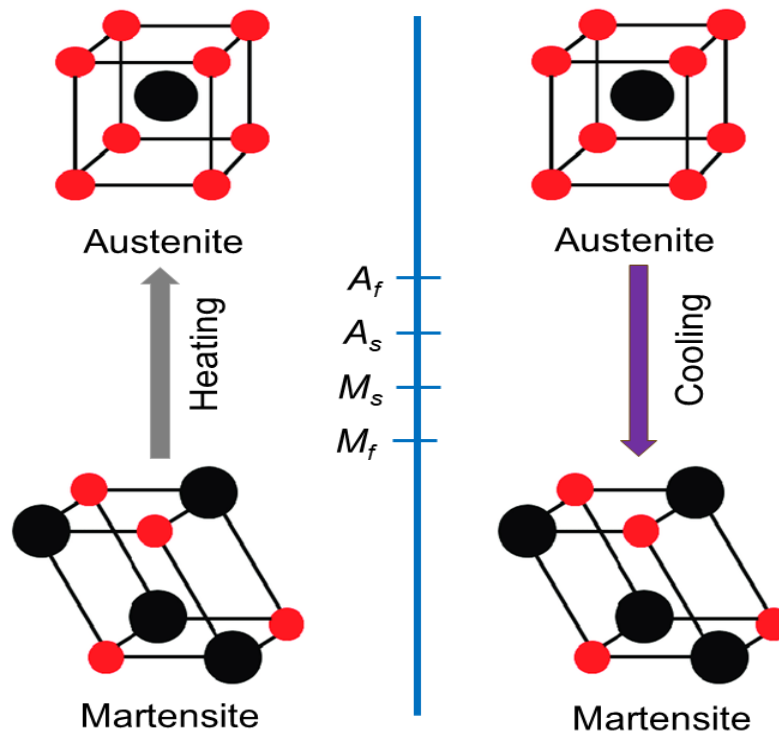


Figure 5.3 Temperature induced phase transformation in Ni-Ti SMAs.

The behavior of shape memory effect is influenced by various factors, including sputtering conditions (such as deposition time, rate, applied power, gas pressure temperature maintained during deposition, and substrate temperature), metallurgical parameters (thermal, and mechanical behavior), Ni-Ti alloy composition ratio (see *Figure 5.4*), contamination, and application-specific conditions (such as environmental temperature, loading condition, stress and strain condition, heating and cooling rates, and so on.)¹³⁸. The electrical and structural characteristics of Ni-Ti are notably important; its high electrical conductivity facilitates Joule heating, which initiates phase transformations between the two lattice phases and results in hysteretic behavior.

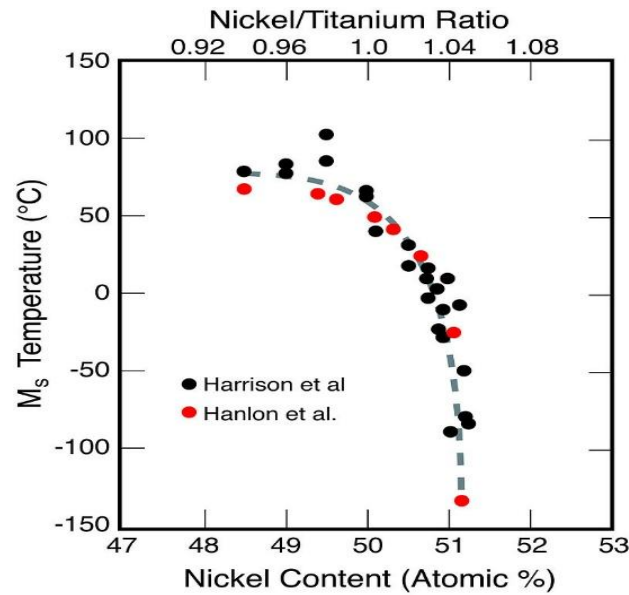


Figure 5.4 Graph of Ni-Ti content ratio (atomic %) versus the temperature change (Taken from ¹³⁹).

5.4 Development of Frequency tunable MEMS sensor

The frequency tuning of MEMS sensor using Ni-Ti SMAs have been presented through temperature-induced phase transformations (see Figure 5.5). This approach enables a single sensor to cover wider frequency ranges without requiring any external excitation, such as DC voltage. The key objective of this research is to induce a mechanical memory effect into the MEMS sensor by utilizing Ni-Ti as a memory element, and to observe the hysteresis effect associated with the SMA phase transformations. To achieve this, a thermomechanical bimorph actuator has been integrated with the MEMS sensor. A change in temperature alone can induce the phase change in SMAs, which passively modify the mechanical properties. These phase transitions between austenite and martensite states significantly alters the mechanical stiffness of the SMA layer, thereby shifting the frequency of the sensor structure ¹⁴⁰. A key design parameter in this system is thickness of the Ni-Ti layer since it has a considerable impact on transformation behavior ¹³⁶. A smart material such as Ni-Ti SMAs have been deposited on the backside of sensor to store and retain information over time, allowing for material-based learning through its inherent memory properties. The following sections provide a detailed discussion on the development of a frequency-tunable MEMS sensor, including modeling, fabrication process, and experimental results.

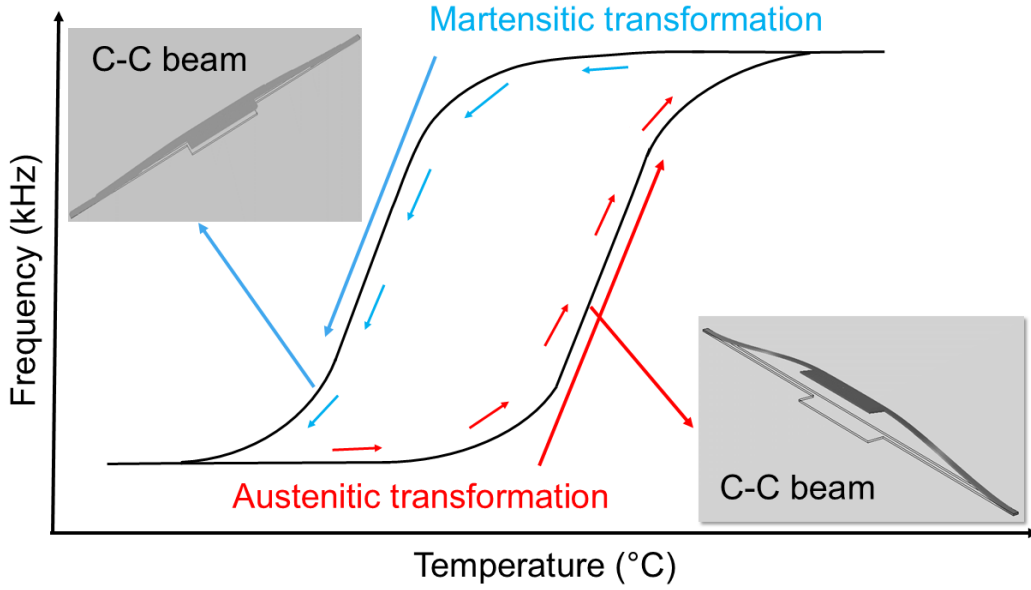


Figure 5.5 Variation of frequency of MEMS sensor in relation to phase transformation temperatures of SMAs.

5.5 Modelling of Ni-Ti shape memory alloys

The model describes, on a functional level, the frequency change that occurs during the material's phase transition. Ni-Ti SMAs undergo phase transitions (martensite - austenite) resulting in changes in mechanical properties such as stiffness, which in turn affect the frequency of MEMS sensor. It is a phenomenological model that describes the frequency shift as a result of temperature-induced phase changes. Therefore, understanding and modeling the temperature-dependent behavior of Ni-Ti is essential. The frequency considering the fraction of Ni-Ti alloy crystals transitioning from martensitic to austenitic phase and from austenitic to martensitic phase is given in equation 5.1, and equation 5.2:

$$f_{MA} = \alpha_{MA}(T) f_{MAF} + (1 - \alpha_{MA}(T)) f_{MAS} \quad (5.1)$$

$$f_{AM} = \alpha_{AM}(T) f_{AMS} + (1 - \alpha_{AM}(T)) f_{AMF} \quad (5.2)$$

To accurately model the frequency behavior of MEMS sensor during phase transformation, it is first necessary to define the frequencies. f_{MAS} , and f_{MAF} represents the frequencies at start and finish of the transformations from martensite to austenite phase, respectively. Similarly, f_{AMS} , and f_{AMF} denotes start and finish frequencies of the transformation from austenite to martensite phase. The material remains largely in its initial phase in the start frequencies, while the finish frequencies

indicate fully transformed state. $\alpha_{MA}(T)$ is the fraction of Ni-Ti alloy crystals in martensitic to austenitic phase during heating. Similarly, $\alpha_{AM}(T)$ denotes the fraction of Ni-Ti alloy crystals in austenitic to martensitic phase during cooling. These functions describe the gradual progression of phase transformations, with values ranging from 0 (no transformation) to 1 (fully transformed), depending on the temperature.

The dependence of phase fraction variables $\alpha_{MA}(T)$ (martensite to austenite transformation), and $\alpha_{AM}(T)$ (austenite to martensite transformation) on temperature is described using a sigmoidal logistic function, as shown in equation 5.3, and equation 5.4:

$$\alpha_{MA}(T) = 1/(1 + e^{(-\beta(T-T_{MA}))}) \quad (5.3)$$

$$\alpha_{AM}(T) = 1/(1 + e^{(-\beta(T-T_{AM}))}) \quad (5.4)$$

This functions are chosen because it smoothly models the gradual transition between martensite and austenite phases over a finite temperature range. The logistic function is commonly used in phenomenological SMA models to represent phase fractions, as it reflects how transformation doesn't occur instantaneously but over a temperature interval, consistent with experimental observations. T_{MA} and T_{AM} denote the transformation temperatures for martensite to austenite phase, and austenite to martensite phase, respectively. T_{MA} is given by: $T_{MA} = (T_{SMA} + T_{FMA})/2$, and T_{AM} is given by: $T_{AM} = (T_{SAM} + T_{FAM})/2$. Here, T_{SMA} and T_{FMA} are start and finish transformation temperatures for martensite to austenite phases, and T_{SAM} and T_{FAM} represent start and finish transformation temperatures for austenite to martensite phases respectively, and β is constant parameter that determines the steepness of logistic curve thereby controlling how sharply the transformation occurs with respect to temperature. The logistic curve provides a mathematically simple yet effective way to describe this gradual transition. A higher β value corresponds to a narrower transformation range, closely approximating an idealized switch, while a lower β reflects a broader, more gradual transformation zone ¹⁴¹.

5.6 Sensor fabrication

The MEMS sensor is fabricated using a combination of bulk and surface micromachining processes ⁵⁸, as detailed in Chapter 4, Section 4.2. The fabrication process involves the deposition of layers, followed by several lithography steps to

define the active regions, and etching to form the structural features. The sensor integrates key components such as thermomechanical actuation elements, piezoresistive sensing, and beam displacement regions, as shown in the SEM image in *Figure 5.6*. After completing the fabrication of sensor structure, a thin film of Ni-Ti SMAs has been deposited on the backside of sensor using sputtering. This final deposition step enables the dynamic frequency tuning by utilizing the temperature-dependent phase transformation behavior of the Ni-Ti alloy.

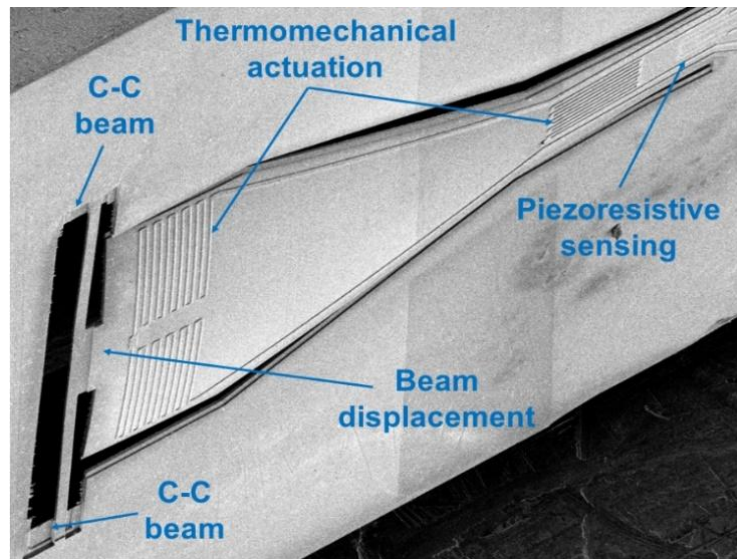


Figure 5.6 SEM image demonstrating insights of a fabricated MEMS sensor including thermomechanical actuation, piezoresistive sensing, beam displacement, and clamped-clamped micromechanical beam (C-C beam).

5.6.1 Deposition of Ni-Ti thin film shape memory alloy MEMS sensor

Sputtering is a deposition technique that enables the formation of thin film coatings composed of sputtered atoms. Various sputtering methods have been reported in the literature for the deposition of Ni-Ti thin films, including magnetron sputtering^{142–144}, co-sputtering^{145–148}, ion beam sputtering¹⁴⁹, laser ablation¹⁵⁰, plasma spray technique, ion plating, and so on¹⁵¹. In this work, precise control over the Ni-Ti ratio and fine-tuning of the overall alloy composition have been achieved using two approaches: i) multi-layer sputtering, where a layer of Ni is deposited first, followed by a separate deposition of Ti in a layer-by-layer fashion, and ii) co-sputtering, where Ni and Ti have been simultaneously deposited from two separate targets.

In the following sections, we will explore the specifics of both approaches, highlighting the challenges encountered and the successful outcomes achieved.

5.6.2 Magnetron sputtering

Magnetron sputtering is a physical vapour deposition (PVD) technique used to produce thin films by ejecting atoms from a solid target material and depositing them onto a substrate. The sputtering source is magnetron, a high-powered vacuum tube in which the electron flow is controlled by an applied magnetic field (see *Figure 5.7*). The process details are as follows: the process begins in a vacuum chamber, ensures the free movement of sputtered particles and minimizes contamination. The target material cathode is positioned within the chamber. The substrate on which the film is deposited is situated in opposite to the target. A magnetron assembly (permanent magnets or electromagnets) is positioned behind the target. To prevent unwanted reactions with the target or substrate during deposition, an inert gas such as argon is supplied into the chamber. The chamber pressure is then regulated to create favorable conditions for plasma formation. An electric field is produced by applying a high voltage between substrate holder (anode) and target (negative cathode).

The electrons emitted from cathode ionize argon gas, forming a plasma composed of positively charged ions and free electrons. The magnetic field created by the magnetron traps electrons near the target surface, enhancing ionization and maintaining a dense plasma. The positively charged argon ions are accelerated towards the negatively charged target, where they bombard the surface, and causing the items to be ejected, a process known as sputtering. These high-energy sputtered atoms travel toward the substrate and condense, forming a thin film. The quality, composition, and thickness of the film are influenced by several parameters, including the applied power, the distance between target and substrate, the gas pressure and the flow rate ^{152–154}.

5.6.2.1 Deposition cycles of Ni-Ti thin films

The magnetron sputtering process is used here to deposit Ni-Ti layers. During this process, multiple layers are deposited, where a layer of Ni is deposited first, followed by a separate deposition of Ti in a layer-by-layer fashion. The deposition is carried out through two distinct set of cycles:

- i) 160 cycles to deposit a 2 μm Ni-Ti layer, with each cycle consisting of 8 nm Ti and 5 nm Ni, resulting in a 13 nm-thick bilayer per cycle,
- ii) 4 sets of 40 cycles each, also used to deposit a 2 μm Ni-Ti layer (see *Table 5.1*).

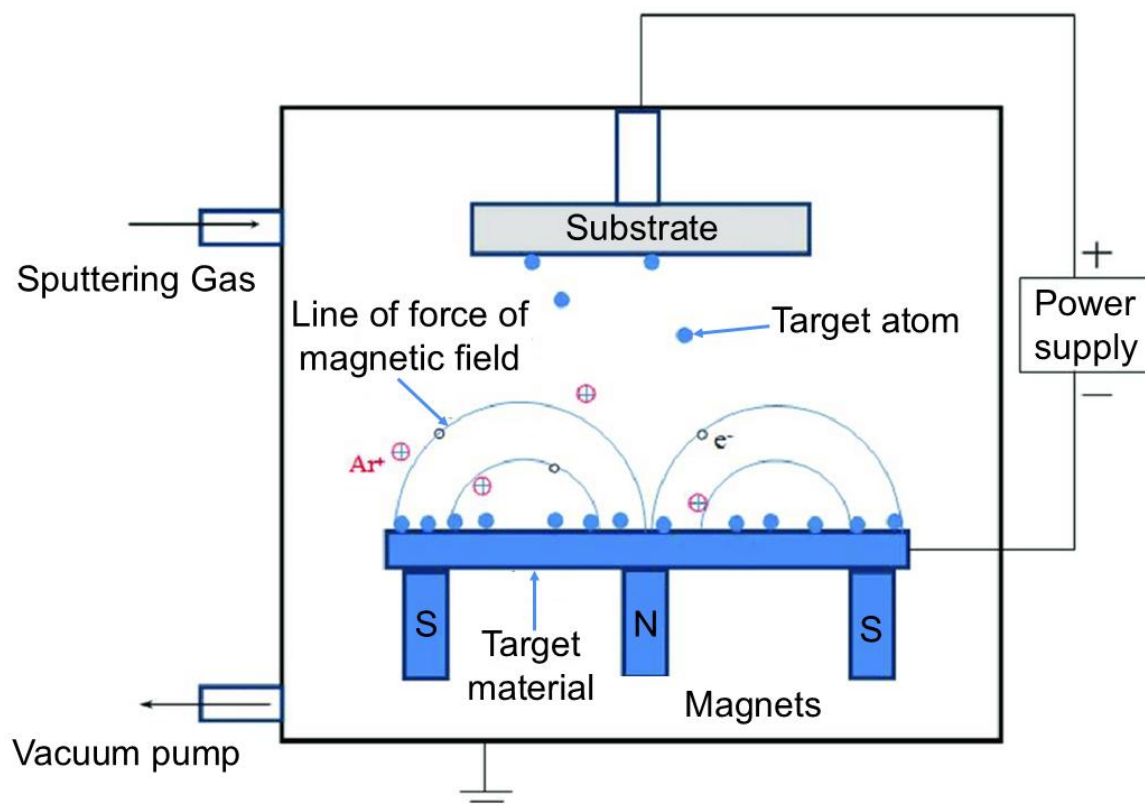


Figure 5.7 Schematic illustration of magnetron-sputtering deposition process (adapted from ¹⁵⁵).

Sr. No	Ti (Atomic %)	Ni (Atomic %)	Thickness (nm)		Deposition (nm)
			Ti (nm)	Ni (nm)	
1	50.8	49.2	7.93	5	500
2	50.4	49.6	7.98	5	500
3	50	50	8.05	5	500
4	49.6	50.4	8.11	5	500

Table 5.1 Different sets of deposition cycles of Ni-Ti thin film by multi-layer sputter deposition technique.

The purpose of using these two distinct sets of cycles is to achieve precise control over the Ni-Ti ratio and overall composition, enhancing the homogeneity of layers during annealing, and to fine-tune the final alloy composition through uniform diffusion. *Figure 5.8* shows a microscopic image of multi-layer sputter deposited MEMS sensor. The yellow regions in the image likely indicate areas where Ni-Ti thin film is not deposited. This may be due to non-uniform deposition, surface contamination such as residual particles that interfered with the adhesion of the Ni-Ti layer. In contrast, the black regions correspond to areas where the Ni-Ti thin film is successfully deposited.

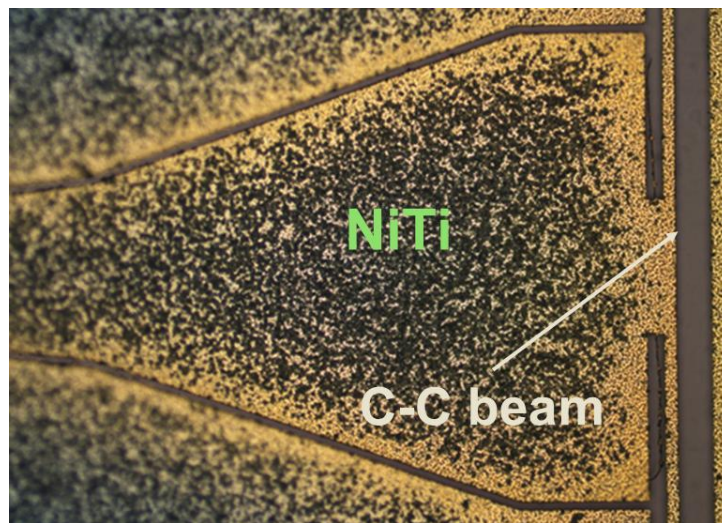


Figure 5.8 Microscopic image of the multi-layer sputter deposition of the Ni-Ti layer using magnetron sputtering.

5.6.2.2 Annealing and effects of internal stresses

Shape memory alloy thin films deposited on unheated substrates are typically amorphous. To induce the crystallinity in the layers, high-temperature thermal treatment (annealing) is required. During annealing, the substrate is heated to a specific temperature for a defined duration in a controlled environment (oxidizing, reducing, and inert). To determine the optimal annealing temperature, initial trials have been conducted at two distinct temperatures: 500°C and 600°C. At 600°C, the sensors are overheated and did not last long (see *Figure 5.9*). The measurements are then carried out at 500°C. The following parameters have been optimized for annealing process: the ramp up temperature is set to 500°C, with ramp rate of 5 degrees per minute and dwell time of 2 hours. Cooling is performed during the remaining period, resulting in a total annealing duration of approximately 6 hours and 30 minutes. The primary objective of annealing is to induce interlayer stresses within the sensor and to

promote homogeneous diffusion of the Ni-Ti thin film onto the substrate. The resulting thin film microstructures and shape memory effect are significantly influenced by the annealing conditions. Additionally, annealing enhances the adhesion of the film to the substrate, likely through formation of thin (40 nm) reaction layers ^{156,157}. However, the presence of reaction products within the film may affect the adhesion ¹⁵⁶. Overall, the interlayer stresses have been induced, facilitating the uniform diffusion of Ni-Ti layer across the substrate.

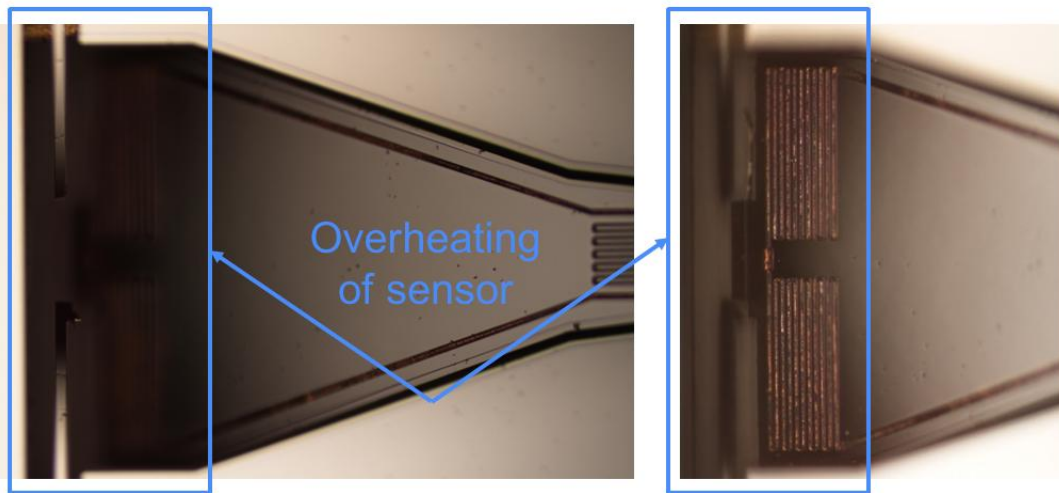


Figure 5.9 Effect of Internal stresses on the sensor dynamics: overheating of sensor at 600°C observed.

Additionally, the sensor chips are annealed in an inert gas environments (with and without N₂ inert gas supply) to assess their impact on the microstructure of multilayer-deposited SMAs. The presence of inert gas showed only a minimal effect on the annealing outcomes of the sensor chips.

Titanium, a highly reactive metal, necessitates a very low base pressure in the sputtering chamber prior to the introduction of argon gas in order to minimize the impurities in the films, which could severely affect the SME ¹⁵⁸. In our process, an argon pressure of 50 mTorr is used. It has also been reported that, by adjusting the target-to-substrate distance, and sputtering gas pressure, Ni-Ti compositional stoichiometry can vary from 47% to 52%, even when using a stoichiometric 50% Ti target ¹⁵⁹. Following the annealing process, martensitic and austenitic phase transformations have been carried out. The martensitic transformation is initiated by cooling the sensor to -20°C for one hour, followed by the measurement of resonance

frequency at room temperature. The austenitic transformation is then performed by heating the sensor to 80°C for 30 minutes (see *Table 5.2*).

Sr. No	Transformations for shape memory effect	Temperature mode	Time duration
1	Martensitic transformation	Cooling at -20°C	1 hour
2	Austenitic transformation	Heating at 80°C	30 minutes

Table 5.2 Phase transformation temperature modes and time durations for SMAs.

5.6.2.3 Challenges encountered following the sequential layer deposition of Ni-Ti SMAs

Several challenges have been occurred following the sequential layer deposition of Ni-Ti SMAs, including non-uniform deposition, the development of self-accommodation morphologies, and the formation of patterns composed of different martensitic variations (see *Figure 5.10*). These variations differ based on the crystallographic planes, and each of these patterns exhibits distinct characteristics in terms of boundary structure and the internal stresses trapped within them ^{160,161}.

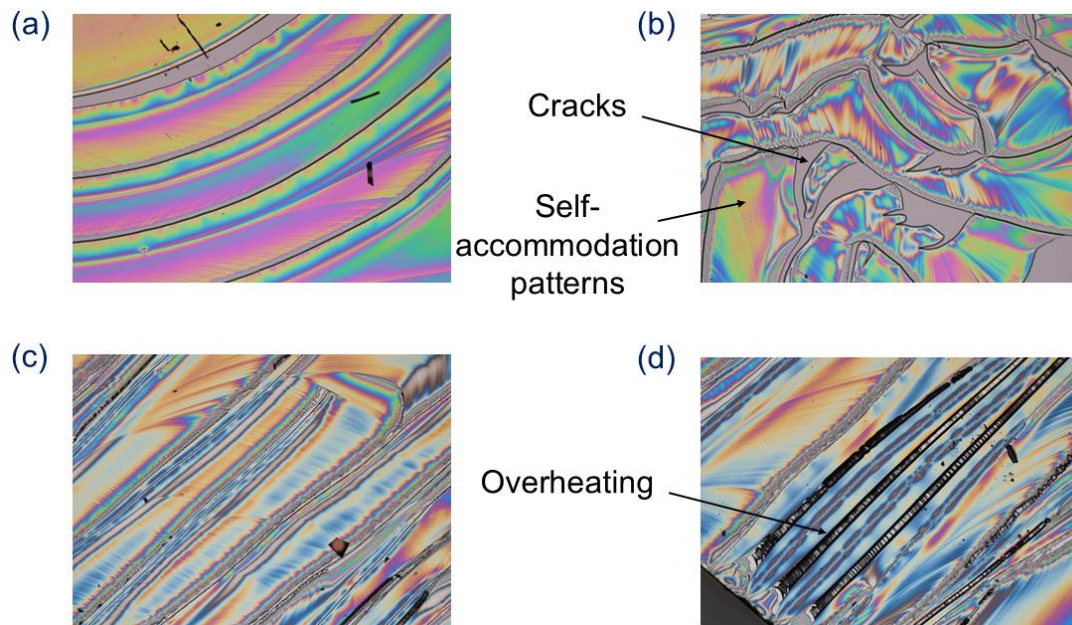


Figure 5.10 Challenges encountered following the deposition of Ni-Ti SMAs via magnetron sputtering.

Additionally, overheating in samples and crack formation have also been observed, which can contribute to discontinuities in the film. During our multi-layer deposition process, we encountered various challenges (can be seen in *Figure 5.10* above), due to which, we are unable to accomplish the desired outcomes. Based on a thorough literature survey, we identified a co-sputtering as a more suitable and promising deposition technique for our work since it allows for the simultaneous deposition of Ni and Ti thin layers, facilitating better control over film deposition and uniformity. The co-sputtering process is discussed in detail in the following section.

5.6.3 Co-sputtering

Co-sputtering is a deposition process that employs multiple sputtering targets to form thin film compositions within a vacuum chamber filled with an inert gas, typically argon (see *Figure 5.11*). This method allows for the fabrication of multilayers through various approaches, such as sputtering individual targets, or simultaneously sputtering multiple targets. In this work, Ni and Ti have been simultaneously deposited on the backside of a sensor from two separate targets. During the deposition process, the sputtering power for each target is independently controlled. The stoichiometry/elemental composition have been regulated by individually optimizing the power and position of each target. Co-sputtering offers better compositional homogeneity as compared to other techniques, making it a highly suitable approach for our application.

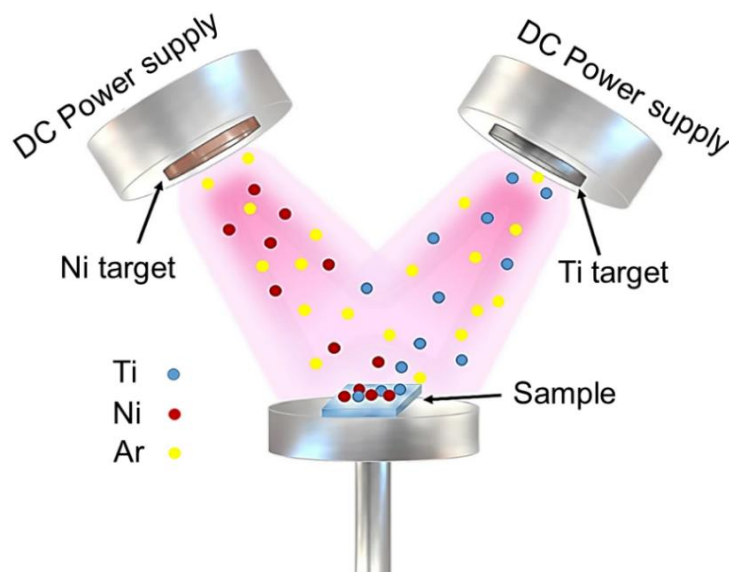


Figure 5.11 Co-sputtering method for the deposition of Ni-Ti thin film shape memory alloy layer (adapted from ¹⁶²).

In this work, the Ni-Ti thin films are deposited in an argon-filled chamber, with an argon flow rate maintained at 50 sccm. Co-sputtering is selected over other deposition processes because it provides superior control over the deposition rate and film composition. During the sputtering process, in-situ heating at 500°C is applied to achieve the homogeneous diffusion among these layers and make these layers more crystalline (see *Figure 5.12 (a)*). This approach results in a fine grain size ¹⁶³, which is essential for inducing the shape memory effect. *Figure 5.12 (b)* presents a microscopic image of the co-sputtered Ni-Ti layer deposited on the backside of the sensor.

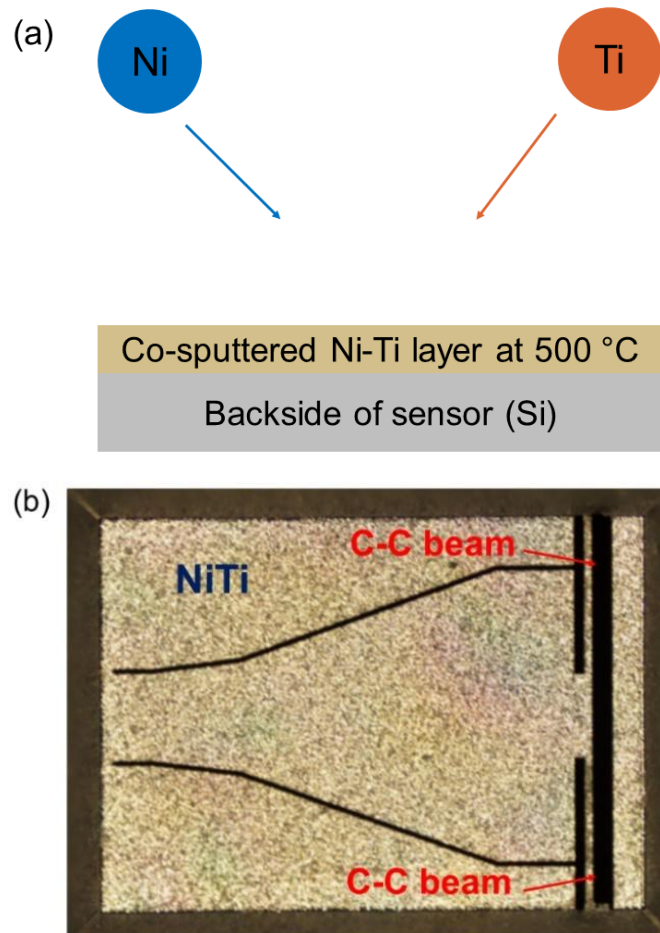


Figure 5.12 (a) Co-sputtering of Ni-Ti thin film layer deposition at 500 °C, and (b) microscopic image of co-sputtered deposited Ni-Ti layer on backside of the sensor.

The crystallization characteristics of Ni-Ti thin films are significantly influenced by film thickness, with variations observed as thickness changes ¹³⁷. As a result, precise control over the Ni-Ti composition, including film thickness, is essential, as even a small changes in composition can have a significant impact on the transformation behavior of Ni-Ti alloys ¹³⁶.

5.6.3.1 Deposition cycles of Ni-Ti thin films

To achieve effective control over the sputter rate, the deposition rates for Ni-Ti layers have been optimized by considering the key parameters, such as sputtering rate of two distinct target elements, distance between substrate and targets, and applied power. For nickel, a power of 70 W is applied, resulting in a deposition rate of 5.64 nm/min, as measured using a profilometer. The power requirements and deposition rates for titanium (Ti) are determined using the density-mass equation.

$$\frac{mTi}{mNi} = \frac{A * tTi * \rho Ti}{A * tNi * \rho Ni} \quad (6.5)$$

The thickness of Ti layer (tTi) is calculated using the relation $tTi = 1.61 * tNi$. Based on this estimates, for titanium, a power of 250 W is applied, resulting in a deposition rate of 9 nm/min. Similar to Ni, the deposition rate of Ti is measured using a profilometer. A 2 μ m Ni-Ti film is deposited using co-sputtering. Consequently, we obtained various Ni-Ti film thicknesses corresponding to specified target power (W) and deposition rates (nm/min) respectively. To study the influence of phase transitions in Ni-Ti thin films on variations in resonance frequency, films with thicknesses of 2 μ m, and 3 μ m have been fabricated using different targeted power and deposition rates respectively (see *Table 5.3*). In MEMS applications, thin reaction layers ($\leq 2 \mu$ m) can significantly affect both adhesion and shape memory effect characteristics ¹⁵⁶.

Sr. No	Target Power (W)		Deposition rate (nm/min)		Ni-Ti film thickness (μ m)
	Ni	Ti	Ni	Ti	
1	70	250	5.64	9	2
2	185	650	14.85	23.90	2
3	325	1000	24.6	39.6	2
4	185	650	14.85	23.90	3
<i>Table 5.3 Conditions for deposition of Ni-Ti thin film by co-sputtering. Here, different deposition rates with different power requirements are used.</i>					

5.6.3.2 Characterization of co-sputtered Ni-Ti thin films

The elemental composition of Ni-Ti thin film has been analyzed using scanning electron microscopy-energy dispersive X-ray spectroscopy (SEM-EDX) (Hitachi S-4800) tool employing a beam acceleration voltage of 25kV, and a take-off angle of 30.7 degrees. *Figure 5.13 (a)* displays the SEM micrograph of Ni-Ti layer, while the elemental composition of Ni and Ti for the presented sensor is determined to be 51.96% (atomic %), and 48.04% (atomic%) respectively, as illustrated in *Figure 5.13 (b)*.

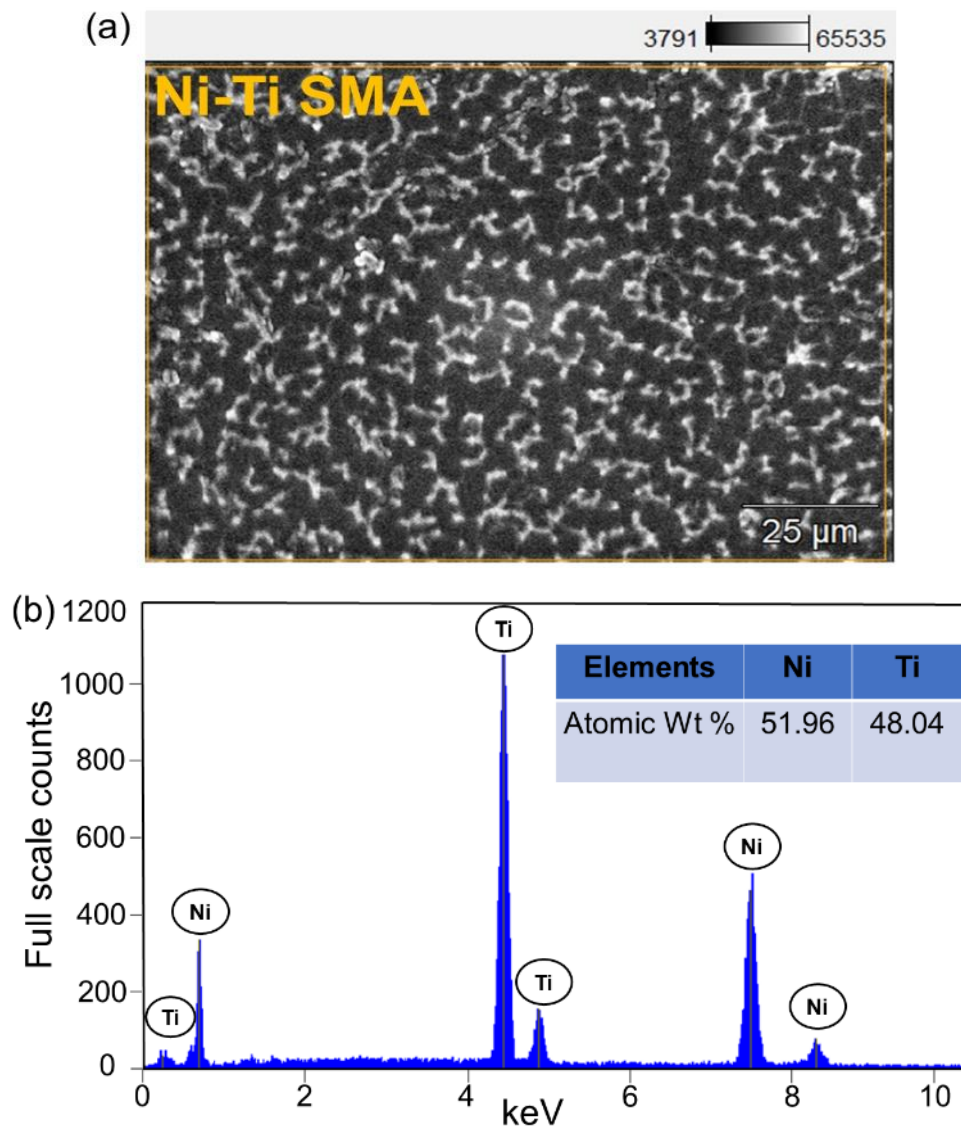


Figure 5.13 (a) SEM micrograph of Ni-Ti layer, and (b) SEM-EDX analysis of Ni-Ti SMA to ascertain the relative compositions of Nickel and Titanium.

5.7 Results and Discussion

5.7.1 Frequency tuning

To investigate phase transformations in Ni-Ti thin films and confirm resonance frequency shifts, a Laser Doppler Vibrometer (velocity range 20 mm/sec, frequency range 20 kHz) from Polytec Micro-System Analyzer MSA-500 (Polytec, Germany) is used. The signals from single-point data acquisition have been analyzed using a fast Fourier transform (FFT) with 12800 lines to extract the amplitude distribution of the sensor's resonance modes. Moreover, to demonstrate the frequency tuning associated with phase transition temperatures of Ni-Ti SMAs, both austenitic and martensitic phase transitions have been carried out. For the austenitic phase transition, MEMS sensors are placed on a PID controller-based hot plate and gradually heated to 45 °C.

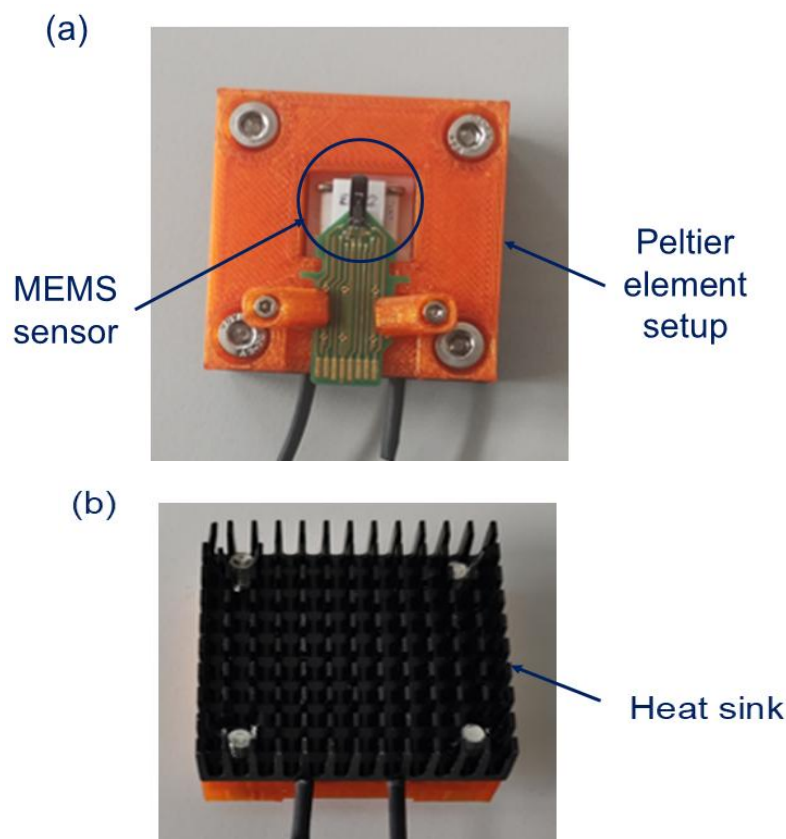


Figure 5.14 Peltier element setup for the martensitic phase transformation of SMAs: (a) front side of the encased Peltier element shows the MEMS sensor, and (b) backside of the encased Peltier element displays the heat sink that provides heat dissipation.

For martensitic transformation, a cooling setup with a Peltier element is used (see *Figure 5.14*). A MEMS sensor has been positioned on a Peltier element, and temperatures are gradually decreased from 45 °C up to -13.8°. At each step, the sensor is allowed to stabilize for several minutes to ensure thermal equilibrium before measurements have been taken.

The temperature measurements are conducted using a PT100 resistance temperature detector (RTD), which confirms to DIN EN 60751 standards. The PT 100 sensor, a resistance temperature detector that measures the temperature through a linear variation in resistance. This behavior arises from the physical characteristics/properties of material (platinum), whose resistance changes with temperature. The temperature is calculated using the following equation:

$$R_T = R_o (1 + \alpha_o T) \quad (6.6)$$

where, R_T is the resistance of RTD at a given temperature (ohms), R_o is the resistance of RTD at reference temperature (ohms), and α_o is the temperature coefficient of resistance (ohms per ohm/degree). In this case, R_o is measured to be 110.4 ohm, α_o is taken as 0.003851. Using these values, the corresponding temperatures have been calculated based on the measured resistances. *Figure 5.15* presents the measured temperatures corresponding to different applied voltage levels.

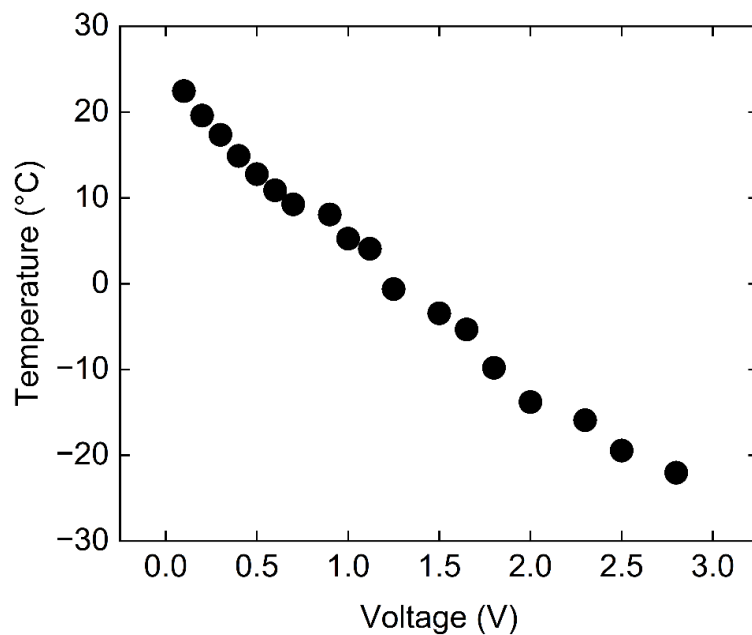


Figure 5.15 Measured temperatures corresponding to different applied voltage levels.

To demonstrate frequency tuning, austenitic phase transitions of Ni-Ti SMAs have been performed on four different sensors, each selected based on distinct initial resonance frequencies. The resonance frequencies of the sensors are measured both before and after Ni-Ti thin film deposition (see *Table 5.4*).

Sr. No	Frequencies before Ni-Ti layer deposition (kHz)	Frequencies after Ni-Ti layer deposition (kHz)
1	5.20	7.0
2	5.0	7.0
3	4.8	8.6
4	7.2	10.6

Table 5.4 Frequencies of the MEMS sensors were measured both before and after Ni-Ti thin film deposition.

5.7.2 Austenitic phase transformation of sensors

MEMS sensors are placed on a PID-controlled hot plate to induce the austenitic phase transition. The temperature is gradually increased up to 80 °C, and the sensors are allowed to stabilize at each temperature step for several minutes to ensure thermal equilibrium. After each temperature increment, the frequency is measured at ambient temperature (see *Figure 5.16*). As shown in *Figure 5.16*, an increase in frequency is observed during the austenitic phase transformation. Specifically, the frequency increased from 5.7 kHz at -20°C to 7.5 kHz at 80°C for sensor 1, from 5.9 kHz to 7.6 kHz for sensor 2, from 7.8 kHz to 9 kHz for sensor 3, and from 9.3 kHz to 10.9 kHz for sensor 4. The increase in the frequency can be due to the increase in stiffness of SMA material as it heats up and transitions into the austenite phase.

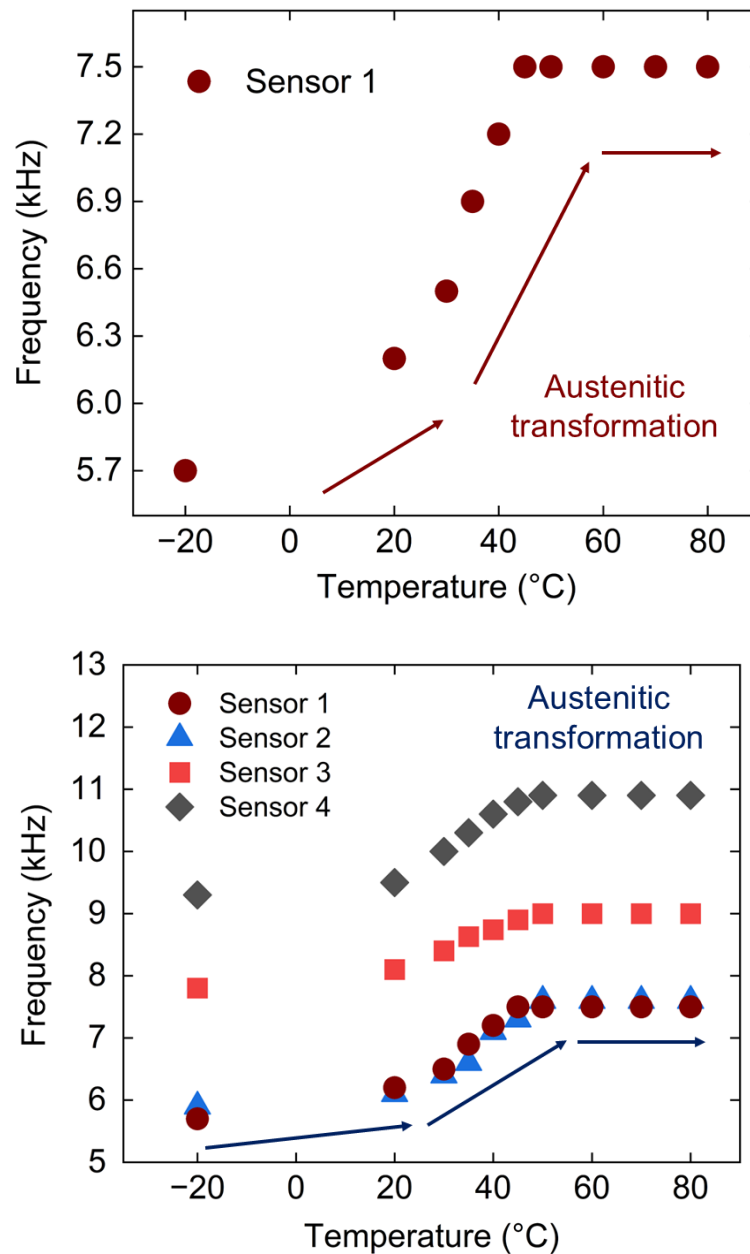


Figure 5.16 Dependence of frequency change with temperature for austenitic phase transformation for different sensors.

5.7.3 Martensitic phase transformation of sensors

Similarly, MEMS sensors are placed on a Peltier element to induce a martensitic phase transformation. The temperature is gradually decreased down to -13.8 °C, and the sensors are allowed to stabilize at each temperature step for several minutes to ensure thermal equilibrium. After each temperature decrement, the frequency is measured at ambient temperature (see Figure 5.17). As shown in Figure 5.17, a decrease in frequency is observed during martensitic phase transformation, from 7.3 kHz at 45°C to 6.85 kHz at -13.8°C for sensor 1, and from 7.3 kHz at 45°C to 6.7 kHz

at -13.8°C for Sensor 2. This behavior aligns with the expected material response during the transition from austenitic to martensitic phase. The reduction in frequency can be due to the decrease in stiffness of the SMA material as it cools and transforms into the martensitic phase.

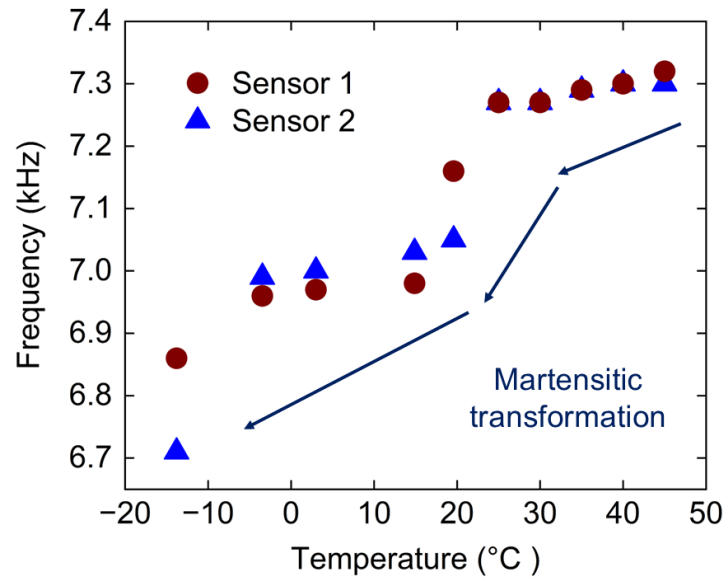


Figure 5.17 Dependence of frequency change with temperature for martensitic phase transformation for different sensors.

5.7.4 Temperature-dependent frequency behavior during austenitic and martensitic phase transformations: Experimental and Simulation comparison

The dependence of frequency on phase transformations have been measured for both austenitic and martensitic transitions. Following each temperature change, the frequency is measured at ambient temperature. During austenitic transformation, the frequency increases from 6.74 kHz at $T = -13.8^{\circ}\text{C}$ to 7.64 kHz at $T = 45^{\circ}\text{C}$. Similarly, during the martensitic transformation, the frequency decreases from 7.64 kHz at $T = 45^{\circ}\text{C}$ to 6.74 kHz at $T = -13.8^{\circ}\text{C}$ (see *Figure 5.18*). This behavior shows the underlying phase transformations of Ni-Ti.

Upon heating from the martensitic phase, the Ni-Ti SMA undergoes a reverse transformation to austenite. This phase change results in an increase in internal stress and mechanical stiffness, leading to a higher pre-deflection in the structure, and consequently, an increase in the frequency. Similarly, during cooling from the austenitic phase, the forward transformation to martensite softens the material, resulting in a reduction in stress and pre-deflection, which causes the frequency to

decrease. These observations demonstrate that the frequency is tunable as a function of temperature. As shown in *Figure 5.18*, the frequency shifts by approximately 1 kHz across the transformation temperature range. The model curve in the figure shows the relationship between temperature and frequency, highlighting the hysteresis associated with the martensite - austenite transformation. In the context of intelligent sensing, such a tunable and hysteretic response enables the sensor to dynamically adjust its operational characteristics based on temperature changes, thereby demonstrating inherent material-level adaptability.

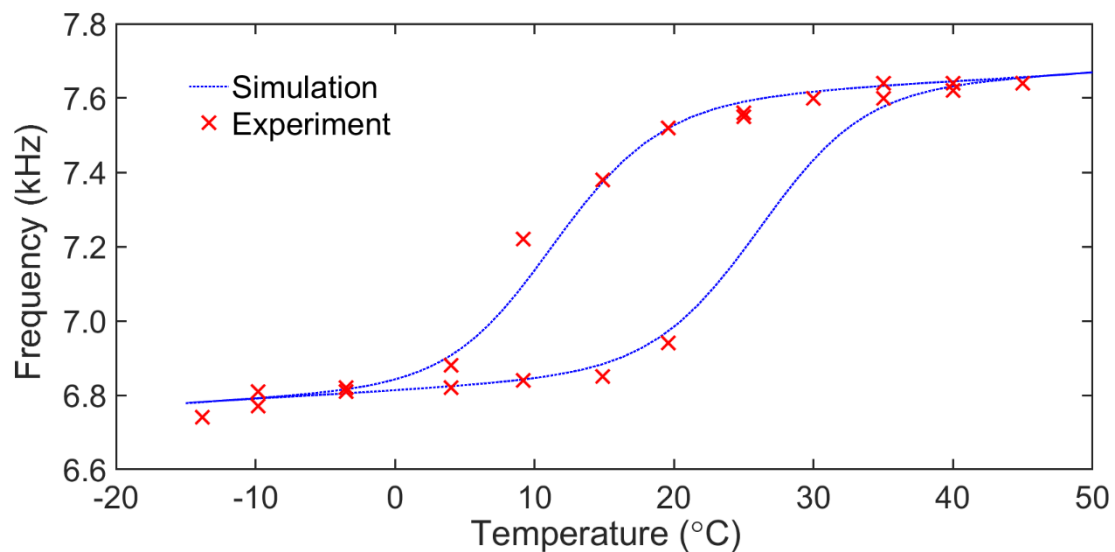
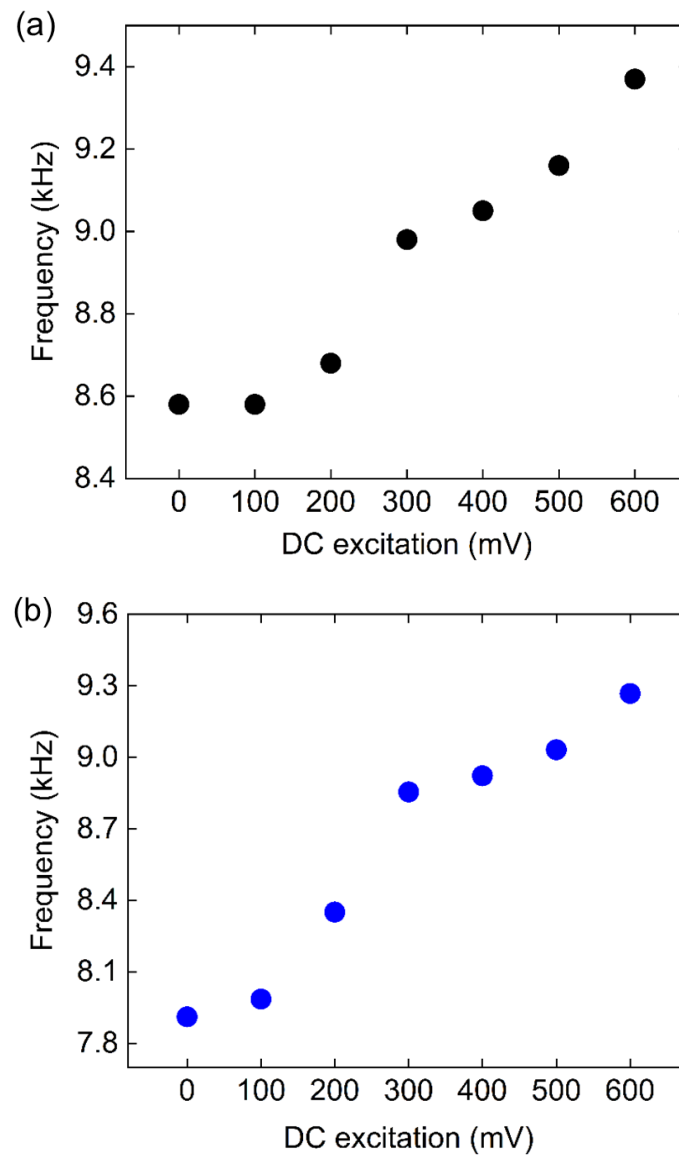


Figure 5.18 Dependence of frequency with temperature exhibits a hysteresis effect: dashed lines represent simulation results, while cross marks indicate experimental results (hysteresis effect observed).

5.8 Pulse Measurements of SMAs

Pulse measurements are conducted on the integrated thermomechanical actuator to evaluate how the frequency varies with temperature. The actuator is excited using pulsed power at frequencies of 1 Hz, 10 Hz, and 100 Hz. A DC voltage of up to 600 mV is applied alongside the heating voltage used for resistive heating. The pulsed input periodically heats the actuator, causing temperature rising and potentially inducing phase transitions in the SMA. Frequency shifts have been observed at all pulse rates, ranging from 8.58 kHz to 9.37 kHz at 1 Hz, from 7.91 kHz to 9.26 kHz at 10 Hz, and from 8.45 kHz to 9.36 kHz at 100 Hz. These frequency shifts reflect changes in the resonant properties of actuator due to temperature dependent effects. This tunable behavior is primarily attributed to the reversible phase transformation of

SMA (between martensite and austenite), which alters the sensor predeflection stiffness and, consequently its natural frequency. The results confirm that the actuator's frequency can be dynamically tuned by adjusting excitation parameters, enabling a single sensor to cover a wider frequency range. *Figures 5.19 (a), (b), (c), and (d)* show the frequency variations at 1 Hz, 10 Hz, 100 Hz, and a combined view of all frequencies, respectively.



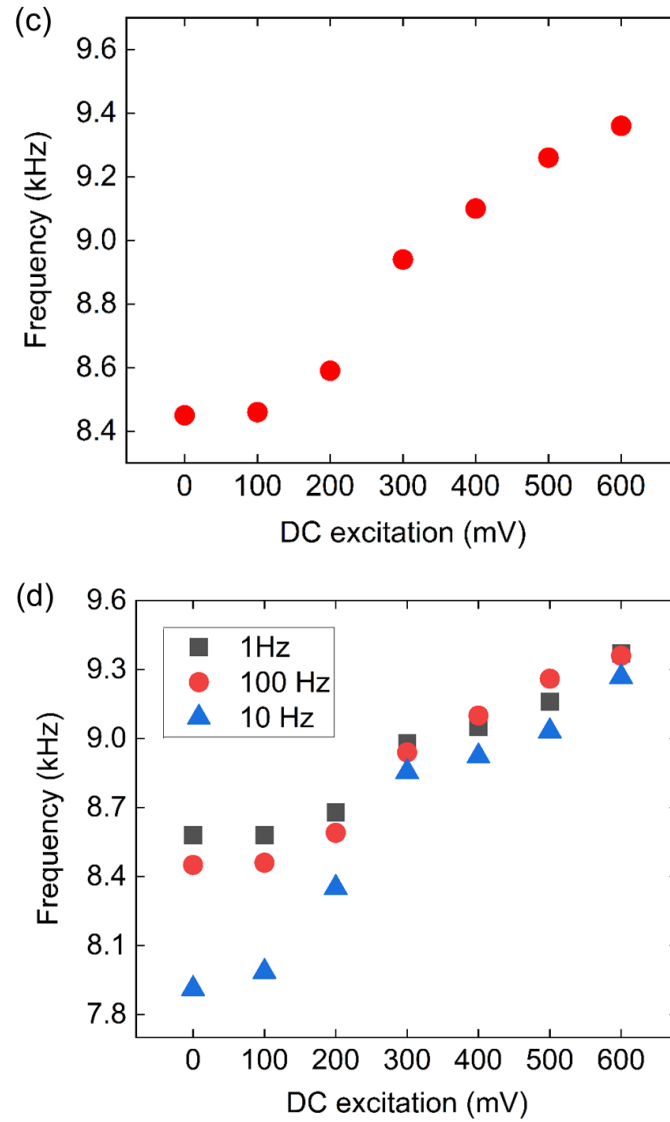


Figure 5.19 Pulse measurements conducted at (a) 1 Hz, (b) 10 Hz, (c) 100 Hz and (d) combination of 1 Hz, 10 Hz and 100 Hz respectively.

Following the austenitic transformation induced through pulse measurements, the Ni-Ti SMAs are cooled to undergo martensitic transformation. The cooling setup is implemented using a Peltier element (see *Figure 5.14*), and the temperatures are measured. To verify that the frequency variation is attributed solely to temperature changes, specifically the austenitic phase transformation, an additional experiment is performed using sensor 3, without applying any supplementary DC voltage. In this case, DC voltage is applied only for resistive heating. A frequency shift from 8.45 kHz to 8.91 kHz has been measured (see *Figure 5.20*). This measurement confirms that the observed frequency variation is caused by temperature effects.

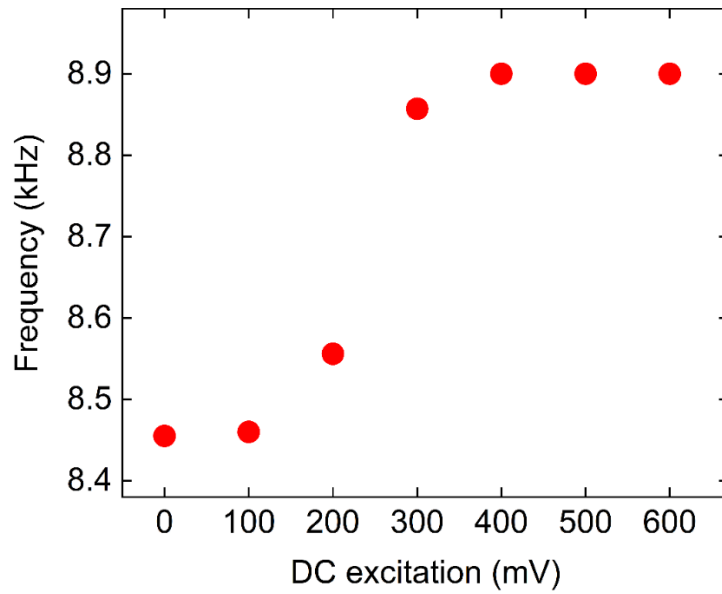


Figure 5.20 Pulse measurement of MEMS sensor conducted at 100 Hz without applying any supplementary DC voltage.

In summary, this chapter presented the development of a frequency-tunable MEMS sensor functionalized with a sputter-deposited Ni-Ti SMA thin film. A frequency tuning of approximately 1 kHz is achieved through controlled temperature variations. This tunability is primarily governed by the reversible phase change between martensite and austenite. By integrating sensing, actuation, and memory-like behavior, the developed MEMS sensor shows key features of an intelligent sensor. The integrated Ni-Ti SMA layer remembers its functional state through its phase transition behavior providing material-level adaptability without relying on external systems.

CHAPTER 6

SUMMARY AND FUTURE WORK

6.1 Summary

This dissertation presented the development of bio-inspired MEMS-based acoustic sensors with dynamically tunable resonance frequencies, aimed at reducing the number of sensors required to cover wider acoustic ranges with a single sensor. The research question investigated how geometric and material-based mechanisms can be utilized to enable the frequency tuning within a single MEMS sensor. To address this, two distinct tuning approaches were explored and experimentally validated:

In the first approach, geometric nonlinearity effects were utilized through incorporating a clamped-clamped micromechanical beam to tune the resonance frequency. This design achieved up to 25% tunability in resonance frequency using low bias voltages (<1 V). A frequency shifts of up to 1.2 kHz were observed, enabling adaptive bandpass characteristics and frequency decomposition functionalities at the sensor level. The sensor was fabricated using surface and bulk micromachining techniques based on scalable on-chip Si-MEMS technology. The resulting micromechanical sensor exhibited a Duffing-like behaviour. The measurement results for electrical and acoustic actuation, as well as the dependence of resonance frequency on applied voltage were thoroughly examined. The experimental results validated the sensor's ability to compensate for fabrication variabilities, such as thickness variation, and demonstrated its application in frequency component analysis of sound signals.

In the second approach, a Ni-Ti shape memory alloy (SMA) thin film was deposited on the backside of the MEMS sensor. A frequency shift of approximately 1 kHz was demonstrated, showing tuning capabilities across the SMA transformation range. The observed frequency shifts under different excitation conditions were strongly correlated with the phase transformation behavior of SMA. The hysteretic behavior of the SMA transition enabled the sensor with memory-like behavior, allowing the sensor to retain specific frequency states over a defined temperature range. This integration of sensing, actuation, and smart material marked a key advancement towards the realization of an intelligent MEMS sensors. The integrated Ni-Ti SMA layer inherently

remembered its functional state through its phase transformation behavior. Such a material-driven response represented a significant step toward the realization of intelligent MEMS sensors that can adapt by themselves without relying on external systems. These geometric and material-based tuning approaches allowed a single MEMS sensor to cover a broader frequency range, reducing the need for multiple sensors.

6.2 Future research directions

The development of the frequency-tunable MEMS sensor opens up various options for future research. Possible approaches include:

1. Resonance frequency adaptation and control

- Develop a controller for real-time adaptation of resonance frequency.
- Adjusting DC bias to compensate for environmental temperature changes.

2. Actuator efficiency improvement

i) Redesign the actuator to enhance the actuation efficiency of the sensor:

To enhance the performance of actuator, a redesign of actuator has been proposed. The COMSOL simulations is utilized to initially assess the displacement and resonance frequency of the sensor. The model geometry is created with the KLayout design tool and subsequently imported into the COMSOL Multiphysics 6.0 simulation environment. Subsequently, the sensor's displacement is estimated, and the resonance frequency is determined. The sensor's displacement is estimated as 13.5 μm , accompanied by a resonance frequency of 4.22 kHz (see *Figure 6.1*).

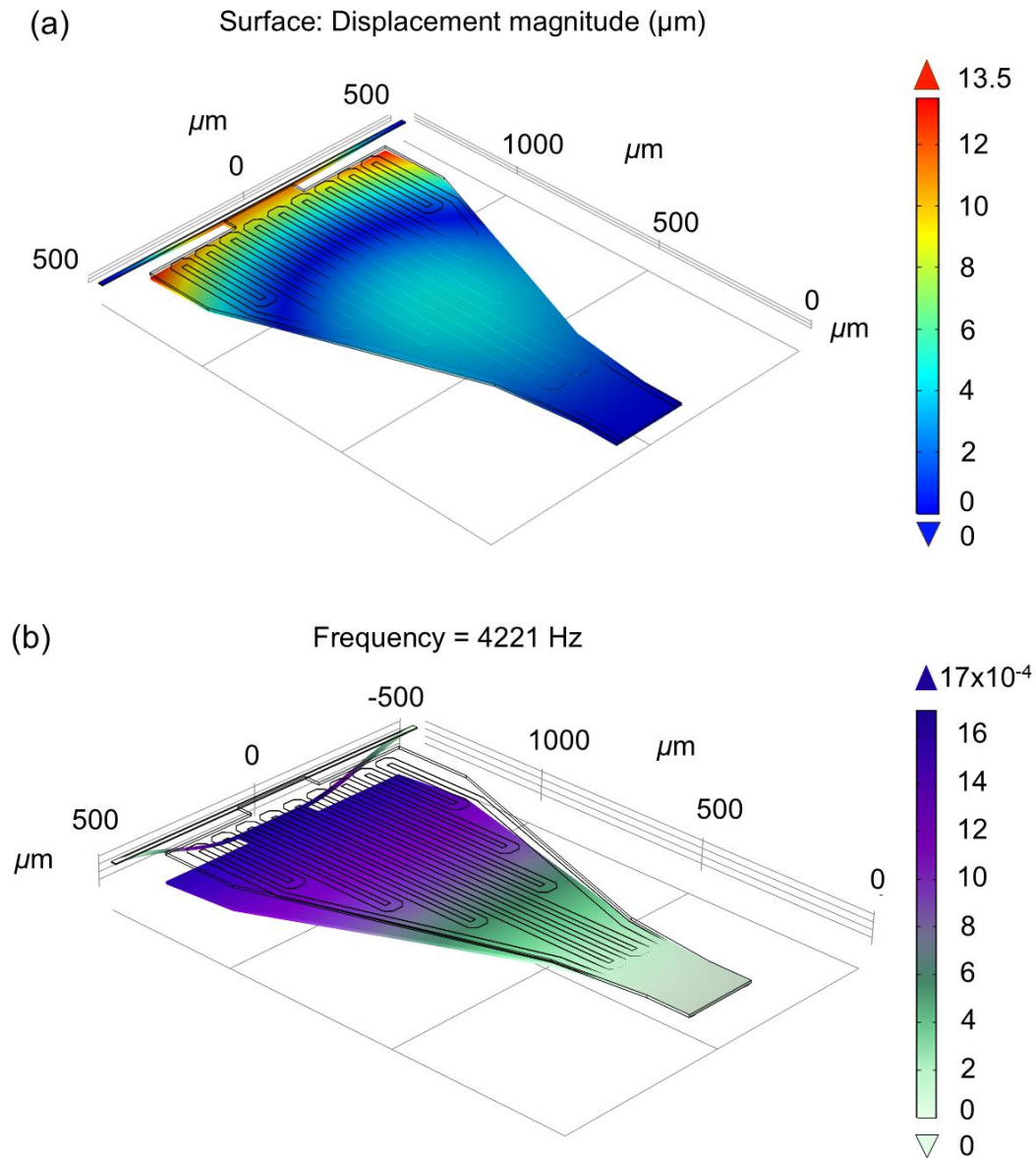


Figure 6.1 shows the finite element simulations using COMSOL multiphysics: (a) static displacement of the sensor, and (b) mode shape for eigenfrequency analysis.

ii) Investigate geometric modifications and explore alternative materials, such as piezoelectric actuation, to improve the performance can be employed in future.

3. Scaling and Integration

- Explore scaling strategies to integrate the sensor suitable for advanced acoustic applications.

By addressing these issues, the suggested sensor can improve the speech and sound processing capabilities, allowing for innovative applications in real-time, and power-efficient, for acoustic applications.

4. Thermomechanical training of shape memory alloy

Thermomechanical training of SMAs is intended to improve their functional properties, including shape memory effect (SME) and superelasticity (SE). This includes the incorporating thermal and mechanical cycling to facilitate and maintain the necessary phase transformations within the material. Thermomechanical training improves the following:

- Phase transformation stability, which is the ability of material to predictably transition between martensite and austenite after repeated cycling.
- Decreases the formation of dislocations, and defects that degrade over time.
- Improves mechanical response. Thus, a proper training of shape memory alloys is an important factor to consider while developing the shape memory effect. As a result, future research will investigate thermomechanical behavior in relation to a variety of training methodologies.

5. Peltier element cooling setup

The cooling system, which was developed with a Peltier element to produce martensitic transformation, has some disadvantages which needs to address in future:

- Temperature uniformity issues: The cooling effect is localized at the junction of the Peltier element, causing non-uniform cooling across the sample.
- Condensation and Frost Formation: Cooling below ambient temperature might cause condensation or frost formations on samples or the Peltier elements.
- Slow Cooling Rates: Peltier elements may not cool samples quickly, limiting their use in applications that need quick temperature changes.

- Environmental Sensitivity: Variations in environmental variables, such as temperature or humidity, might influence the performance of the Peltier element, requiring additional control measures.

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LIST OF PUBLICATIONS

1. Journal publications

1. **V. Gubbi**, T. Ivanov, K. Ved, C. Lenk, and M. Ziegler, “Bio-inspired acoustic MEMS sensor with tunable resonance frequency”, *Sensors and Actuators A: Physical Journal*, Feb, 2025.
2. C. Lenk, D. Beer, A. Männchen, J. Küller, S. Durstewitz, **V. Gubbi**, T. Ivanov, and M. Ziegler, “Bio-inspired Microphone - The MEMS Cochlea”, *Akustik Journal*, Jun 2023.
3. **V. Gubbi**, T. Ivanov, C. Lenk, and M. Ziegler, “Shape memory behavior in co-sputter deposited NiTi- based frequency tunable MEMS sensor”, In preparation.

2. Conference proceedings

1. S. Durstewitz, K. Ved, **V. Gubbi**, T. Ivanov, M. Ziegler, and C. Lenk, “ Acoustic MEMS Sensor System to emulate properties of the human hearing”, *BMT 2024, 58th Annual Conference of the German Society for Biomedical Engineering*, 2024.
2. C. Lenk, T. Ivanov, S. Durstewitz, K. Ved, **V. Gubbi**, and M. Ziegler “An Adaptive Acoustic Neuromorphic Auditory System”, *IEEE Nanotechnology Materials and Devices Conference (NMDC)*, Dec 2023.
3. E. Khan, C. Lenk, A. Männchen, J. Küller, D. Beer, **V. Gubbi**, T. Ivanov, and M. Ziegler, “Influence of Sensor Design on Bio-Inspired, Adaptive Acoustic Sensing”, *DAGA - Mar 2023, 49th Conference for Acoustics, Hamburg, Germany*.
4. **V. Gubbi**, T. Ivanov, K. Ved, C. Lenk, and M. Ziegler, “Tunable Piezoresistive MEMS resonator for bio-inspired acoustic sensing with thermomechanical bimorph actuation”, *International conference on Micro and Nano Engineering EUROSENSORS 2022 (MNE)*, Leuven, Belgium, Sep 2022.
5. C. Lenk, T. Ivanov, **V. Gubbi**, K. Ved, M. Ziegler, T. Fritsch, J. Küller, and D. Beer, “Bio-inspired, non-linear and adaptive acoustic sensing - Study of sensor design”, *DAGA – Mar 2022, 48th Conference for Acoustics, Germany*.

3. Poster presentations

1. **V. Gubbi**, T. Ivanov, K. Ved, C. Lenk, and M. Ziegler, “Tuning of bio-inspired MEMS resonator”, International summer school - Bio-inspired Information Pathways, University of Groningen, Netherlands, 2023.
2. **V. Gubbi**, T. Ivanov, K. Ved, C. Lenk, and M. Ziegler, “Tuning of bio-inspired MEMS Resonator”, Joint symposium IMNeuS23 with CRC 1459 (Intelligent Matter), Münster, Germany, 2023.
3. **V. Gubbi**, T. Ivanov, K. Ved, C. Lenk, and M. Ziegler, “Tunable Piezoresistive MEMS resonator for bio-inspired acoustic sensing with thermomechanical bimorph actuation”, PhD day at Technische Universität Ilmenau, Germany, 2022.
4. Folke Rolf, K. Ved, **V. Gubbi**, C. Lenk, T. Ivanov, Philip Hovel, Thomas Meurer, and M. Ziegler, “Tuning of bioinspired MEMS cochlea for nonlinearities”, International colorline workshop - Bio-inspired Information Pathways, Norway, 2022.
5. **V. Gubbi**, T. Ivanov, K. Ved, C. Lenk, and M. Ziegler, “Tuning of bio-inspired MEMS Resonator”, PhD day at Technische Universität Ilmenau, Germany, 2022.

INFORMATION ON THE AMOUNT OF THE PERSONAL CONTRIBUTION FOR PUBLICATIONS/MANUSCRIPTS WITH SEVERAL AUTHORS

1. Publication/manuscript: Bio-inspired acoustic MEMS sensor with tunable resonance frequency, Sensors and Actuators A: Physical Journal, Feb, 2025.

Authors: **Vishal Gubbi**, Tzvetan Ivanov, Kalpan Ved, Claudia Lenk, Martin Ziegler

The own contribution: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation.

2. Publication/manuscript: Bio-inspired Microphone - The MEMS Cochlea”, Akustik Journal, Jun 2023.

Authors: C. Lenk, D. Beer, A. Männchen, J. Küller, S. Durstewitz, **V. Gubbi**, T. Ivanov, and M. Ziegler

The own contribution: Numerical simulations using COMSOL, fabrication of sensor

3. Publication/manuscript: Shape memory behavior in co-sputter deposited NiTi-based frequency tunable MEMS sensor”, In preparation.

Authors: **V. Gubbi**, T. Ivanov, C. Lenk, and M. Ziegler

The own contribution: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation.

4. Publication/manuscript: Acoustic MEMS Sensor System to emulate properties of the human hearing, BMT 2024, 58th Annual Conference of the German Society for Biomedical Engineering, 2024.

Authors: S. Durstewitz, K. Ved, **V. Gubbi**, T. Ivanov, M. Ziegler, and C. Lenk

The own contribution: fabrication of sensor (wire bonding)

5. Publication/manuscript: An Adaptive Acoustic Neuromorphic Auditory System, IEEE Nanotechnology Materials and Devices Conference (NMDC), Dec 2023.

Authors: C. Lenk, T. Ivanov, S. Durstewitz, K. Ved, **V. Gubbi**, and M. Ziegler

The own contribution: fabrication of sensor (wire bonding)

6. Publication/manuscript: Influence of Sensor Design on Bio-Inspired, Adaptive Acoustic Sensing, DAGA - Mar 2023, 49th Conference for Acoustics, Hamburg, Germany.

Authors: E. Khan, C. Lenk, A. Männchen, J. Küller, D. Beer, **V. Gubbi**, T. Ivanov, and M. Ziegler

The own contribution: Numerical simulations using COMSOL, fabrication of sensor

7. Publication/manuscript: Tunable Piezoresistive MEMS resonator for bio-inspired acoustic sensing with thermomechanical bimorph actuation, International conference on Micro and Nano Engineering EUROSENSORS 2022 (MNE), Leuven, Belgium, Sep 2022.

Authors: **V. Gubbi**, T. Ivanov, K. Ved, C. Lenk, and M. Ziegler

The own contribution: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation.

8. Publication/manuscript: Bio-inspired, non-linear and adaptive acoustic sensing - Study of sensor design”, DAGA – Mar 2022, 48th Conference for Acoustics, Germany.

Authors: C. Lenk, T. Ivanov, **V. Gubbi**, K. Ved, M. Ziegler, T. Fritsch, J. Küller, and D. Beer

The own contribution: Numerical simulations using COMSOL, fabrication of sensor

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APPENDIX (ALL PARAMETER VALUES USED IN COMSOL MULTIPHYSICS SIMULATIONS)

Properties of Materials used

1. Silicon

- Density – $2.329 \cdot 10^3 \text{ kg/m}^3$
- Melting point – $1415 \text{ }^\circ\text{C}$
- Thermal conductivity – $131 \text{ W/(m}^\circ\text{K)}$
- Coefficient of thermal expansion – $2.6 \cdot 10^{-6} \text{ (1/K)}$
- Band gap – 1.12 eV
- Dielectric constant – 11.9
- Youngs modulus – 170 GPa
- Yield strength – $7.0 \cdot 10^9 \text{ Pa}$
- Relative permittivity – 11.7
- Heat capacity – $700 \text{ J/Kg}^\circ\text{K}$
- Coefficient of thermal expansion – $2.61 \cdot 10^{-6} \text{ K}^{-1}$
- Electrical conductivity – $1 \cdot 10^{-12} \text{ S/m}$
- Poissons ratio – 0.22

2. Aluminium

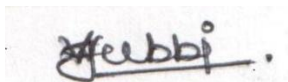
- Aluminium – $1 \text{ }\mu\text{m}$
- Density – 2694 kg/m^3
- Coefficient of thermal expansion – $23.3 \cdot 10^{-6} \text{ K}^{-1}$
- Thermal conductivity – $236 \text{ Wm}^{-1}\text{K}^{-1}$
- Relative permittivity – $10 \cdot 10^{-12}$
- Poissons ratio – 0.33
- Youngs modulus – 70 GPa

3. Tuning beam thickness range used for the simulation – $2.5 \text{ }\mu\text{m}$ to $3 \text{ }\mu\text{m}$

4. Sensing beam thickness range used for the simulation – $5 \text{ }\mu\text{m}$ to $7 \text{ }\mu\text{m}$

DECLARATION OF AUTHORSHIP

I herewith declare that this thesis and the corresponding research were composed and authored by myself. The work complies with the DFG guidelines for safeguarding good scientific practice. All content and ideas drawn directly or indirectly from external sources are clearly indicated. This thesis has not been published or been submitted to any other institution and all related research items that have been published in peer-review journals are indicated as such. I declare that no academic degree has been withdrawn from me.

A handwritten signature in dark ink, appearing to read 'Heubbi', followed by a period.

Kiel, June, 2025