NEMS Based Actuation and Sensing

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Abstract

This article offers rigorous overview of diverse transduction methods that have enabled successful development of Micro/Nanoelectromechanical Systems (MEMS/NEMS) components and devices used for sensing and actuation. The paper focuses on providing educational insights on the transductions used in MEMS/NEMS, and curates the latest applications and design trends. The review begins by classifying various transduction techniques, explaining cross-domain couplings, presents an underlying working principles and governing equations that drive transducer operation. Both actuation and sensing modes of each transduction method are exclusively explained and discussed, accompanied by the latest case study examples and references. The article provides detailed scientific insights into the widely used transduction techniques in MEMS/NEMS, addresses effective comparative performance of one over another (force, displacement, resonance frequency, quality factor, noise, nonlinearity, energy requirements, etc.) The paper also highlights emerging materials and fabrication platforms using which these transducers are developed.
Transduction in MEMS/NEMS Based Actuation and Sensing

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Abstract—This article offers rigorous overview of diverse transduction methods that have enabled successful development of Micro/Nanoelectromechanical Systems (MEMS/NEMS) components and devices used for sensing and actuation. The paper focuses on providing educational insights on the transductions used in MEMS/NEMS, and curates the latest applications and design trends. The review begins by classifying various transduction techniques, explaining cross-domain couplings, presents an underlying working principles and governing equations that drive transducer operation. Both actuation and sensing modes of each transduction method are exclusively explained and discussed, accompanied by the latest case study examples and references. The article provides detailed scientific insights into the widely used transduction techniques in MEMS/NEMS, addresses effective comparative performance of one over another (force, displacement, resonance frequency, quality factor, noise, nonlinearity, energy requirements, etc.) The paper also highlights emerging materials and fabrication platforms using which these transducers are developed.

Index Terms—Acoustic, Actuators, Electro-magnetic, Electro-thermal MEMS, NEMS, Optical, Piezoelectric, Piezo resistive, Resonators, Sensors, Transducers

I. INTRODUCTION

Micro- and nanoelectromechanical systems (MEMS/NEMS) are rapidly emerging technologies that enable ultra-miniaturization and high-volume integration of mechanical, electrical, acoustic, fluidic, magnetic, and optical sub/components at the micro- and nanoscale [1], [2]. This technology offers significant potential for various applications in research and industry, including medical, 5G/6G, environmental, energy, aerospace, consumer electronics, and automotive systems [3]–[6]. MEMS/NEMS technologies have the potential to revolutionize various industries by enabling compact, efficient, and high-performance solutions for a wide range of applications. The field of MEMS/NEMS continues to advance rapidly, and it is expected to play a critical role in shaping the future of many industries and applications. One of the key characteristics of MEMS/NEMS components is their ability to transduce energy from one form to another. This means that physical quantities, biological and/or chemical processes can be analyzed in terms of proportional electrical signals, allowing for precise quantification and measurement. MEMS/NEMS transducers, which include both actuators and sensors, are being widely deployed in a wide range of products, such as robotic machines [7], industrial equipment [8], lab instruments [9], mini-satellites [10], optics [11], RF devices in smartphones [12], biomedical instruments [13], defense systems [14], resource exploration tools [15], advanced automobiles, and consumer electronics, among others [16], [17].

This paper aims to provide a comprehensive scientific review of the details of various transduction methods utilized in MEMS/NEMS. MEMS/NEMS actuators are capable of converting applied electrical energy into mechanical action, such as generating motion, force, and/or electro-magnetic fields. Meanwhile, MEMS/NEMS sensors are designed to detect changes in physical quantities that can be measured. MEMS/NEMS transducers have numerous advantages, including low cost due to high volume fabrication, low energy consumption, ultra-small size and weight, high precision, high accuracy and resolution, stability, and most importantly, compatibility for very large scale integration (VLSI) with microelectronics. The transductions used in MEMS/NEMS can be broadly categorized into the following: electrostatic, electro-thermal, electro-magnetic, piezoelectric (acoustic), capacitive, piezo-resistive, resonant (mode-localized), and optical. The paper is therefore structured as follows: firstly, a
model of a solid-state transducer is presented along with the principal equations and an example showing transformation between mechanical and electrical domain. Then, various transduction techniques for actuation are introduced along with their associated principles, equations, applications, relative merits and shortcomings. Next, a separate section on sensors is included, which outlines different sensing mechanisms, equations, advantages and disadvantages, and applications. This section also highlights possible combination of sensing methods that combine with actuation in a single transducer. As applicable, figures and tables are included to aid comprehension of the principle of operation, and comparative performance of transducers (both actuators and sensors). Lastly, the paper concludes with final remarks and scientific insights, intended to facilitate the understanding of the readers on the field advancements.

II. SOLID-STATE MODEL OF A TRANSDUCER

Fig. 1(a) shows a solid-state model of a transducer with a one degree of freedom (DoF) mass-spring-damper. A net force in this model is \( F = Ma \), where \( a = \frac{dx}{dt^2} \) is an acceleration, \( v = \frac{dx}{dt} \) is the velocity and \( x \) is the displacement from its equilibrium position. \( F_s \), \( F_c \) and \( F_e \) are restoring, damping and net external force, respectively. Summing the forces,

\[
\sum F = F_e - F_c - F_s = Ma. \tag{1}
\]

And,

\[
F_e = M \frac{dx}{dt^2} + C \frac{dx}{dt} + Kx. \tag{2}
\]

The transducer acts an actuators and converts an input energy, such as an electric signal into a force vector (electrostatic, magnetic, mechanical, or thermal) applied to a component, structure, or device, resulting in its movement, \( x \). For example, in Fig. 1(a), proof mass experiences the net electrostatic force, \( F_e \) as a result of an applied electric load to the transducer. The force generated could be static or time-varying, depending on the nature of electric load applied. Once the device moves, sensing mechanisms such as capacitive/piezo resistive (discussed later) are employed to convert the movement back into an electric signal. An analogy between electrical and mechanical domains is shown in Fig. 1(b) to understand the transduction, where a mechanical device can be represented with the electrical elements, and mapping of mechanical quantities into electrical ones is given. Following, we review the various techniques used in MEMS/NEMS transducers.

III. ELECTROSTATIC

Fig. 2(a) depicts an electromechanical transducer, specifically a parallel plate actuator that uses electrostatic actuation [18], [19]. In a static scenario, the behavior of the mechanical structure is governed by an electric load, or DC polarization voltage \( (V) \), in conjunction with the mechanical restoring force. The DC voltage applies a static electrostatic force to the mechanical structure, which causes it to deflect to a new position. In a dynamic situation, such as a resonator, the electric load consists of a DC polarization voltage \( (V) \) and an AC voltage \( (V_{ac}) \). The DC component exerts an electrostatic force on the mechanical structure, which deflects it to a new equilibrium position, and the AC component causes the structure to vibrate around this equilibrium position.

Mathematically, the nominal capacitance of this structure is given by \( C_0 = \frac{eA}{d} \), where \( e \), \( A \), and \( d \) represent the permittivity, nominal electrode area, and capacitive air gap, respectively. The change in capacitance due to motion is

\[
\Delta C = \frac{eA}{d-x} = CV^2, \tag{2}
\]

where \( V \) is an applied voltage across the capacitor. A net electrostatic force therefore is

\[
F = \frac{1}{2} \frac{eA}{(d-x)^2} V^2. \tag{3}
\]

Fig. 2(b) shows a structure of a parallel plate in-plane gap/area modulated transducer, also referred as comb-drive. A nominal capacitance here is \( C_0 = \frac{eL}{d} \), where \( e, L, t \) and \( d \) are the permittivity, overlap length, plate thickness and air gap, respectively. Assume that the dimensions are \( L_p = 100\mu m \) (plate length), \( L = 80\mu m \), \( d = 1\mu m \), \( t = 2\mu m \). Then, in case of an area modulation, where, applied voltages are \( V_1 = V_2 = V = 1V \), \( V_r = 0V \), capacitance varies as

\[
C = \frac{eL}{(d-x)} t = x, \tag{4}
\]

The electrostatic force is

\[
F_e \approx \frac{d}{dV^2}. \tag{5}
\]

In the case of a gap modulation, applied voltages are \( V_1 = 0V \), \( V_2 = 1V \), \( V_r = 0V \), capacitance varies as

\[
C = \frac{eL}{(d-x)} t, \tag{6}
\]

The force is linear (independent of a motion) for an area modulator, whereas it is nonlinear for a gap modulated transducer. Additionally, transduction factor, \( \eta \) for gap and area modulated parallel plate electrostatic transducers are \( \eta_e \approx \frac{d}{d^2} V^2 \) and \( \eta_h \approx \frac{d}{d^2} \), respectively. By comparison, we note that for same device dimensions, and applied voltages, an electrostatic force and the transduction factor in the gap modulated transducer are relatively larger (by factor \( L/2d \)) compared to an area modulated transducer. Relatively larger transduction factor, \( \eta \) results in higher motional admittance in the dynamic (resonant) applications. Comb-drive structure [20] is however preferred due to larger in-plane displacements (up to 150 \( \mu m \)) and force in comb-drive mode is relatively independent of motion. Referring to Fig. 1(a), for a static case (i.e. \( x \) is independent of time), restoring force is

\[
F_s = K_d x, \tag{7}
\]

and \( F_{eff} = K_{nm} + K_e \) is an effective spring constant, where \( K_{nm} \) and \( K_e \) are mechanical and electrical spring constants, respectively. And,

\[
K_e = -\frac{\varepsilon A}{(d-x)^2} V^2. \tag{8}
\]

Negative effective value of \( K_e \) denotes spring softening, allowing frequency tuning in electrostatic transducers [21]. Simple designs, ultra-low power, integration with CMOS on the same silicon die, and faster response are some of the advantages of electrostatic transduction. However, this transduction requires deep sub-micro/nano air-gaps to
Dielectric-constant (High-transduction, which involves filling the air-gap with a high-integration with CMOS is required. Internal dielectric to the large motional impedance of resonators, their micro-resonators through one/two-port transmission voltage can be generated across the electrodes for a given selecting a material with a high dielectric constant, a higher greater the amount of energy that can be stored. Therefore, by electric field is applied. The higher the dielectric constant, the measure of its ability to store electrical energy when an material, which can be measured as a voltage across the in the formation of an electric dipole moment in the dielectric electrodes. The magnitude of the voltage generated depends material, which can be measured as a voltage across the across the electrodes, the material polarizes, creating a charge separation within the material. This charge separation results in the formation of an electric dipole moment in the dielectric material, which can be measured as a voltage across the electrodes. The magnitude of the voltage generated depends on the dielectric constant of the material and the applied electric field strength. The dielectric constant of a material is a measure of its ability to store electrical energy when an electric field is applied. The higher the dielectric constant, the greater the amount of energy that can be stored. Therefore, by selecting a material with a high dielectric constant, a higher voltage can be generated across the electrodes for a given electric field strength.

An air-gap electrostatic transduction is a method to test micro-resonators through one/two-port transmission measurements, and single/differential actuation. However, due to the large motional impedance of resonators, their integration with CMOS is required. Internal dielectric transduction, which involves filling the air-gap with a high-dielectric-constant (High-K) material (Fig. 3(a)) offers much higher transduction efficiency [31]. As the schematic of Fig. 3(c) shows, a Bulk Longitudinal Resonator using Si3N4 as the dielectric material and single crystal silicon as the resonator, demonstrates internal electrostatic transduction, with a measured \( Q \) of 2,100 in air and a 9.2 kΩ motional impedance at a frequency of 121 MHz [32]. The use of high-k dielectric material, such as Al2O3, has also been shown to benefit the performance of electroacoustic transducers, such as Capacitive Micromachined Ultrasonic Transducers (cMUT) [33]. A nanometer-thick dielectric material in very thin films (< 10 nm) using atomic layer deposition (ALD) techniques and fully compatible with silicon manufacturing, are promising for micro and nano-electromechanical devices [34].

Dielectric electrostatic transduction has several advantages over common air-gap transduction. By utilizing dielectric materials, smaller capacitive gaps can be achieved, which can help prevent issues such as pull-in and stiction that are commonly associated with air-gap transducers. The high dielectric permittivity of dielectric materials can also enhance the driving force and capacitive sensing capabilities of the transducers [35]. For extremely high frequency (HF) bands of the radio spectrum, such as microwave oscillators for low-power clocking in microprocessors, internal dielectric transduction of longitudinal bulk-mode MEMS silicon resonators at 4.51 GHz has been demonstrated [31]. The efficiency of this transduction mechanism was shown to increase as the thickness of the dielectric approaches the acoustic half wavelength in silicon. By placing the dielectric films at positions of maximum strain (or minimum displacement) in the resonator operating at 4.51 GHz has shown to achieve a significant signal enhancement of 9.8 dB. This suggests that careful optimization of the dielectric thickness and placement can lead to improved performance and higher resonant frequencies in capacitive devices utilizing dielectric electrostatic transduction.

Use of an internal dielectric transduction has recently been shown to demonstrate pull-in voltage reduction in air-gap transducers [36]. Due to enhanced transduction efficiency, this transduction method was also compared with the piezoelectric transduction (discussed below) which on the first order is impeded by material quality and decrease of its electromechanical coupling when the piezoelectric film thickness is reduced below 100 nm [35]. Despite of the advantages as listed above, we observed only few recent research on internal dielectric transduction [36]. This is probably due to the challenges linked to the large feedthrough capacitor (large dielectric constant) and integration with CMOS.

IV. ELECTRO-THERMAL

Thermal actuators function based on the principle of Joule heating, wherein the application of a voltage causes a current to flow through the actuator material, generating heat due to its inherent resistance. The resulting increase in temperature leads to thermal expansion, causing displacement of the actuator. The deformation of the actuator may also be utilized to actuate other components. The electro-thermal force generated can be mathematically expressed as \( F_{th} = \alpha_T AE(T - T_0) \), here \( \alpha_T, E, A, T, \) and \( T_0 \) are coefficient of thermal expansion (CTE), young’s modulus, cross-section area of material, initial and final temperature, respectively.

MEMS thermal actuators are commonly fabricated using materials such as gold, platinum, or a thermally sensitive material such as silicon/polysilicon [37], [38]. The principle of operation involves utilizing the thermal expansion or contraction of materials to create mechanical motion. In particular, the actuator comprises a thin film of a thermally sensitive material that is heated using an electrical current. As a result of the heating, the material undergoes thermal expansion, leading to displacement of the actuator in a predefined direction.
The micro actuator depicted in Fig. 4(a) consists of two arms connected to a base at the end of each arm. This schematic design illustrates a simple U-shaped thermal actuator in which one arm is narrow (hot) and the other is wide (cold). These arms are connected in series to an electrical circuit in which the current generates a Joule heating effect. Due to the different arm configurations, more heat is generated in the narrow arm, leading to differential thermal expansion. This creates a bending moment, resulting in an arc-like deflection towards the cold arm. The narrow (hot) arm, with a smaller cross-section, has a larger electrical resistance, resulting in higher temperatures and greater thermal expansion. Conversely, the wider (cold) arm has a lower resistance, and the heat is dissipated through a larger surface area. The flexure beam located at the base of the cold arm facilitates bending deflection. Fig. 4(b) illustrates an alternative design for a thermal actuator, intended for out-of-plane applications. In this configuration, a micro heater is supplied with a current, which generates heat and creates a temperature gradient in the heater. The two materials used in the actuator also experience a temperature gradient across their surfaces, resulting in the generation of a thermal force in the structure. Due to differences in the coefficient of thermal expansion (CTE) of the materials used, the actuator bends as shown in the Fig. 4(b).

In the dynamic thermal actuation and sensing, the microbeam is subjected to an electric current, which induces an increase in temperature and subsequent thermal expansion, leading to displacement. Simultaneously, an AC current is applied to the beam, causing temperature fluctuations and alternating thermal stress in the structure, leading to actuation in its resonant mode. The mechanical vibrations in the actuator beam cause variation in resistance ($\Delta R/R$), which in turn modulates the beam's resistance, producing time-varying current. The frequency of this current can be measured. Transducers based on this principle are referred to as ‘‘Thermal-Piezoresistive’’ (TPR) transducers and have been implemented for detecting and measuring the concentration of ultra-fine particulate matter (PM) [39].

Various other configurations of electro thermal actuators are widely reported in literature, including thermal buckling actuators/chevron-shaped/V-shaped actuators [38], [40]–[43]. It is to be noted that as bimorph actuators consist of two thin films of different materials bonded together (Fig. 4(b)), while unimorph actuators consist of a single thin film with a built-in stress gradient (Fig. 4(a)). Both types of actuators can generate precise and repeatable motions.

Thermal actuators provide several advantages over other types of actuators, including their high efficiency, ability to operate at low voltages, and small size, which makes them useful for applications like thermostats, and safety shut offs. Thermal actuators are also capable of producing large force generation and displacement, and can convert electrical energy into motion at the microscale [44]. MEMS thermal actuators are used for microgrippers [45], micro- and nanopositioners, scanning probes, active thermal control for microsatellites, micromirrors [46], linear and rotary microengines, micropumps in microfluidics, ultra-precise movement in medical devices, and control of RF tunable filters, switches, optical attenuators, and gyroscopes [47]–[49]. MEMS thermal actuators can be fabricated using standard microfabrication techniques, making them compatible with other MEMS devices, and they can be designed to consume lower power. However, their relatively slow response time [50] compared to other types of MEMS actuators and their requirement for precise temperature control are some of their limitations [41], [51]. Multiphysics simulation is used in the design of thermal actuators aids to ensure that the generated heat is high enough to cause thermal expansion but not hot enough to cause permanent deformation.

V. ELECTRO-MAGNETIC

MEMS magnetic actuators utilize the Lorentz force to convert an electric current into a mechanical output [49], [52]. This force is generated by the interaction between the magnetic field of a permanent magnet and current in the coil, and is given by the equation $\vec{F} = q\vec{v} \times \vec{B}$, where, $q$, $\vec{v}$ and $\vec{B}$ represent charge, velocity and magnetic field, respectively. As seen in Fig. 5, when a current is passed through a beam fixed at both ends and placed in a magnetic field, the beam experiences a Lorentz force due to the magnetic force acting on the moving charged particles within the beam. The force is at right angles to the direction of the current and the magnetic field, resulting in displacement of the particles within the beam. This force can be calculated using equation (4) that relates the magnetic field ($\vec{B}$), current ($I$), and length ($L$) of the conductor. $\theta$ is the angle between current and the magnetic field.

$$|\vec{F}| = |I L \times \vec{B}| = B i L \cdot \sin \theta.$$  (4)

Electromagnetic micro-actuators, such as micro-pumps and micro-valves, can produce displacements up to a few $\mu$m within a few seconds [53], [54]. MEMS electromagnetic actuators offer advantages such as small size, low power consumption, high precision, and integration with electronics. Other examples of MEMS electromagnetic actuators include microscale solenoids, microelectromechanical switches, micro-actuators for optical fiber alignment, and micro-relays, which have applications in biomedical, optical communications, and consumer electronics [55], [56]. Specific example applications are fabrication of bonded magnet for electromagnetic membrane actuators to drive micro-pumps [57], PDMS based electromagnetic actuator membrane with embedded magnetic particles in polymer composite [58], and electromagnetic micro-actuator with silicon membrane for fluids pump in drug delivery system [59].

VI. PIEZOELECTRIC

Piezoelectricity is an interaction between the solid mechanics and electrostatics that models piezoelectric phenomena. Piezoelectricity is a material property to become electrically polarized under strain and stress. This
phenomenon is observed in certain materials. Piezoelectric materials generate an electric charge in response to an applied mechanical stress, and vice-versa, thereby providing direct 2-way signal transduction from the mechanical domain to the electrical domain, and vice-versa. Therefore, piezoelectric transducers can be used both as a sensor and actuator. Piezoelectric-based transduction provides a relatively direct, linear actuation and sensing than its electrostatic counterpart.

When a Piezoelectric material converts strain into an electric polarization, it is called direct piezoelectric effect. When a Piezoelectric material converts an electric polarization into the proportionate strain it is called inverse piezoelectric effect. The governing equations that relates strain $\varepsilon$, electric displacement $D$, stress $S$, and electric field, $E$ are given in equation (5), [60]–[62]:

$$\varepsilon = s_E S + d^T E$$
$$D = d S + \varepsilon_0 \varepsilon_r E$$

A set of matrix equations can be used to model the piezoelectric coupling using the strain–charge ($d$-form) or stress–charge ($\varepsilon$-form) relationship. These two forms can be converted to each other. The equation (5) shows $d$-form. The material parameters $s_E$, $d$, and $\varepsilon_r$ are the compliance, coupling matrix, and relative permittivity, respectively, and superscript $T$ is the transpose. The first part of the equation (5) states that the stress field and electric field produce strain. The second part of the equation states that the electric polarization is generated by the stress field and electric field. The second term in the first part of the equation is an electric contribution to the strain. An electromechanical coupling coefficient, $k_2^2$, in piezoelectric transduction is given as [63]

$$k_2^2 \approx \frac{E_p d_{31}^2}{\varepsilon}$$

And also,

$$k_2^2 \approx \frac{\pi^2 C_m}{8 C_0}$$

Here, $E_p$, $d_{31}^2$, and $\varepsilon$ are Young’s modulus, piezoelectric coefficient, and strain in the piezoelectric material. $C_m$ and $C_0$ are motional and static capacitance of a piezo-transducer. In piezoelectric transduction, $k_2^2$ is relatively higher ($\approx 2-3\%$) as compared to its electrostatic counterpart ($\approx 0.1\%$). The piezoelectric materials are high energy density materials and energy density of the piezoelectric actuator scales well with decreasing dimensions (beneficial for ultra-miniaturization) [64]. In addition, robustness comes from the fact that high electric fields are confined inside solid-state material(s).

Commonly used thin films to manifest relatively larger piezoelectricity are Lead zirconate titanate (PZT), Aluminum nitride (AlN), Lithium niobate (LiNbO3), quartz, polyvinylidene fluoride (PVDF) and Zinc oxide (ZnO). Wafer-scale film thickness can be about 200 nm [65]–[73].

A. Piezo acoustic

Coupling between piezoelectricity and acoustics has allowed piezoelectric materials to be used as acoustic transducers. Here, the piezoelectric material is excited with an electrical stimulus in the frequency range (kHz to MHz range). Such harmonic electrical excitation produces structural vibrations in the piezoelectric material which generates acoustic waves in the surrounding fluid media (air or liquids), see Fig. 6 [74]. Reverse principle also holds true where an electrical signal is generated as an output in response to the reception of an acoustic wave by the transducer. The piezoelectric micromachined ultrasound transducer (PMUT) has gained growing attention recently [75]. This transduction is used in several applications such as hydrophones [76], phased array microphones, speakers, bio-imaging/ultrasound, inkjet droplet actuators, sonar transducers [77]–[81].

B. Bulk and Surface Acoustic Wave (BAW and SAW)

Bulk acoustic wave (BAW) transducers are composed of a thin piezoelectric layer placed between two electrodes, with a substrate acting as a supporting structure (Fig. 6(a), 6(b) and Fig. 6(d) [82]. Application of a voltage to the electrodes causes the piezoelectric layer to expand and contract, generating acoustic waves in the substrate. These waves propagate back and forth between the substrate and the piezoelectric layer, resulting in a standing wave that resonates at a particular frequency. Surface acoustic wave (SAW) transducers, as shown in Fig. 6(c) consist of electrodes placed on the surface of a substrate, and the acoustic waves propagate along the substrate's surface [82]–[84]. SAW transducers are fabricated by depositing a thin film of piezoelectric material on top of a substrate, such as lithium niobate or quartz. Electrodes are then deposited on the piezoelectric material, and a specific pattern is etched into the electrodes to create a vibrating structure. Application of an electrical signal to the electrodes results in the piezoelectric material's expansion and contraction, producing surface acoustic waves that propagate along the substrate's surface. These waves reflect back and forth between the electrodes, creating a standing wave that resonates at a specific frequency.

The resonant frequency of BAW/SAW transducers is determined by the thickness of the piezoelectric layer, the substrate's material properties (e.g., acoustic velocity), and the electrode pattern. By manipulating these parameters, the resonant frequency can be adjusted to a particular value. BAW/SAW transducers offer high stability, low energy consumption, and high $Q$, making them ideal for filtering and amplifying signals in wireless communication systems. They are also used in a variety of sensing applications, such as pressure and temperature sensors [63], [82], [85]–[87].

Piezoelectric transduction is used in a variety of device, including piezo-acoustic transducers (e.g., microphones and speakers), mirrors, gyroscopes, accelerometers, micro-grippers, gas sensors, and RF filters and oscillators, inkjet print heads, switching devices, ultrasound medical imaging, MEMS-based logic, and energy harvesting [63], [64], [67], [71], [73], [76], [82]–[90] [13]. However, manufacturing challenges have limited the widespread commercial use of miniaturized piezoelectric devices. Nevertheless, some commercial applications, such as Avago Technologies’ (formerly Agilent/HP) FBAR filters, are already available [91], [92]. High-frequency FBAR resonators fabricated from aluminum nitride (AlN) thin films on Si wafers are commonly used as filters in consumer devices, such as smartphones [13]. One limitation of piezoelectric transduction is the material
quality, as the electromechanical coupling decreases when the piezoelectric film thickness is less than 100 nm [1].

VII. SENSING

MEMS/NEMS based sensing techniques have revolutionized the field of sensing by allowing for the development of miniature, precise, low-power, high-volume, and relatively low-cost sensors. In this section, we discuss some of the popular sensing/detection mechanism in MEMS/NEMS.

A. Piezo-resistive

Piezo-resistivity refers to the change in a material’s conductivity that occurs in response to an applied stress. Piezo-resistance, usually associated with semiconductors results from the strain-induced alteration of the material’s band structure and accompanying changes in carrier mobility and number density. The piezo-resistive effect is based on the change in electron mobility in the material caused by the mechanical stress. Piezo-resistors are relatively easy to manufacture using common semiconductor processes, are inherently shielded from electromagnetic interference, and usually straightforward to be implemented with electronic interface. Pressure sensors based on the piezo-resistive effect were some of the first MEMS devices to be mass produced [93], [94]. Piezo resistive devices, however, usually consume more power and generate more electrical noise than capacitive sensors, which are displacing piezo resistive devices in some applications. Fig. 7 (a) shows configurations of the transducers that facilitate detection and measurement of physical quantities/bio/chemical traces by means of detecting change in the resistance. When the structure moves, the change in embedded piezo resistors occurs. This change in the resistance, \( \Delta R \), is proportional to the applied strain, \( \varepsilon \), and is given as, \( \Delta R = G \varepsilon R \), where \( G \) is the gauge factor, and \( R \) is the nominal resistance. Subsequently, this change in resistance is converted into the proportionate voltage difference through Wheatstone bridge circuit as seen in Fig. 7(b).

In MEMS/NEMS, semiconductors such as poly/silicon are commonly used as a structural material. An output of a sensor can be quantified as \( \Delta R / R \) (normalized). Here, \( \Delta R \) is the change in resistance and \( R \) is the nominal resistance of the material (poly/silicon/germanium) used as a resistor. Other common materials used for piezo-resistive sensors also include certain polymers. The pressure sensors [93], humidity sensors [95], force sensors [94] and strain gauges [96] are few of the examples that use piezo-resistive effect. The piezo-resistive effect has also been utilized in mass sensing application that used thermal actuation [97]. Unlike the piezoelectric effect, piezo-resistivity is not reversible, so an applied current does not induce a stress (unless other secondary effects are present, such as heating). Piezo-resistive sensing is often seen combined with actuation schemes such as electrostatic and thermal [98], [99].

B. Capacitive

Capacitive sensing has been widely used in pressure sensors, and capacitive pressure sensors have replaced now piezo resistive pressure sensors that were few of the first pressure sensors to come to market. Capacitive sensing includes a structure of a parallel plate capacitance as given by the equation \( C = \frac{\varepsilon A}{d} \) (refer also section III). As capacitance is inversely proportional to the distance between the plates, sensing of very small displacements is extremely accurate. Referring to Fig. 2, and Fig. 7(a), the change in capacitance can be converted into proportionate change in voltage/current and be measured. Touchscreens [100], accelerometers [101], gyroscopes, pressure sensors [102], and humidity sensors [103] are few of the examples that use capacitive sensing. Capacitive sensing offers several advantages over other sensing technologies, including high sensitivity, ultra-low power, small size, and high reliability. A variety of applications such as detecting tilt [100], particles [104], biomarker in exhaled breath [105] and gas [89] have been demonstrated. Capacitive sensing is often seen combined with electrostatic actuation [106], [107] and sometimes with thermal actuation [108], [109].

C. Thermal

MEMS thermal sensors operate on the principle of converting a temperature change into an electrical signal, allowing for precise and real-time temperature monitoring and control [110]. One common MEMS-based thermal transducer is the thermoelectric sensor [111], which is used for both temperature sensing and power generation (see Fig. 8(a)). In this type of sensor, the temperature difference between two conductors produces an electromotive force, which can be measured by means of voltage difference and correlated to the temperature. The thermoelectric transducer can operate in a wide range of temperatures, making it useful for various applications, including automotive, aerospace, and industrial settings. Another type of MEMS thermal transducer is the thermal resistor [112], which works by measuring the change in electrical resistance with temperature. The thermal resistor can be made using thin-film deposition techniques, allowing for the production of miniature sensors that can be integrated into various devices and systems. The thermal resistor is commonly used in consumer electronics, such as smartphones and laptops, for temperature monitoring. Another type of thermal sensor is the micro-bolometer. As seen in the schematic of Fig. 8(b), microbolometers are MEMS-based thermal transducers that detect the infrared radiation emitted by objects [113], [114]. They consist of a small pixel with a thin-film absorber that heats up when exposed to infrared radiation. The change in resistance is measured to determine the temperature. When microbolometers are arranged in a 2-D array, a thermo-graph of the object can be determined using a microbolometer based uncooled infrared sensor [23].

Surface acoustic wave (SAW) devices are MEMS-based thermal transducers that work based on the change in the propagation velocity of acoustic waves with temperature [115]–[117]. When the temperature changes, the velocity of the acoustic wave changes, which can be measured and correlated to the temperature difference. Resonant cantilevers are MEMS-based thermal transducers that work based on the change in the resonant frequency, \( f \) with temperature, \( \Delta T \). When the temperature changes, the resonant frequency of the cantilever changes, which can be detected and correlated to the temperature difference \( S = \Delta f / \Delta T \), \( S \) is the sensitivity. Applications of thermal sensors are mass flow metering [110],
wind sensing [110], detection of hydrogen gas in vehicle interiors [118], measuring liquid flow down to 0.05 μl/min [112].

D. Electromagnetic

MEMS electromagnetic sensors detect changes in electromagnetic fields and convert them into electrical signals that can be processed and analyzed [119]. These sensors are based on the principle of electromagnetic induction, which states that when a conductor is exposed to a changing magnetic field, an electric current is induced in the conductor. MEMS electromagnetic sensors typically consist of a magnetic core, which generates a magnetic field, and a coil, which detects changes in the magnetic field. When an external magnetic field is applied to the sensor, it induces an electric current in the coil, which produces a voltage that can be measured and analyzed.

One example of a MEMS electromagnetic sensor is a magnetic field sensor, which is used to measure the strength and direction of magnetic fields [120]. These sensors are commonly used in a variety of applications, including navigation, robotics, and automotive systems. Another type is Hall Effect Sensors that utilize the Hall Effect to measure magnetic fields. A voltage is generated across a conductor when it is subjected to a magnetic field perpendicular to the direction of current flow. Hall Effect sensors are commonly used for position, speed, and current sensing [121]. Few other examples are Magneto-Optical Sensors that use the Faraday Effect to measure magnetic fields. When light passes through a material in the presence of a magnetic field, the polarization of the light is rotated. Magneto-optical sensors are commonly used for non-destructive testing and magnetic field imaging. Magneto-resistive Sensors, capable to detect weaker magnetic field measure changes in resistance caused by a magnetic field [90]. As the magnetic field changes, the resistance of the sensor changes, which can be measured to determine the strength and direction of the field. Magneto-resistive sensors are commonly used for compasses, position sensing, and current sensing. Also, Eddy Current Sensors use the principles of electromagnetic induction to measure changes in magnetic fields [122]. A changing magnetic field induces a current in a conductor, which can be measured to determine the strength and direction of the field. Eddy current sensors are commonly used for non-destructive testing and proximity sensing. Electromagnetic transduction is also seen to be in energy harvesting applications [123]–[125]. Other demonstrated applications are human respiratory monitoring [126].

E. Resonant sensing

Resonant sensing is a prevalent technique that utilizes the resonant properties of a structure to detect changes in physical parameters such as mass [127], position [60], strain/stress [128], pressure/force [75], electric field, temperature, acceleration/tilt, and others [129]. This technology has been extensively researched and is being applied in various fields, including chemical sensing, medical diagnostics, environmental monitoring, and natural resources exploration [39], [130]. One of the most commonly used MEMS/NEMS resonant sensor is the resonant poly/silicon beam sensor, comprising a thin flexible beam that resonates at its natural frequency (Fig. 9(a)). When a load is applied to the beam, the resonant frequency changes, and this change can be used to determine the magnitude and direction of the force. With reference to section III, a charge voltage relationship in an electrostatic capacitor is $Q = CV$ and $(V = V_\text{ac} + V_\text{dc})$. Subsequently, a current through the structure is given as

$$i \approx C_0 \frac{\partial V_\text{ac}}{\partial t} + V_\text{dc} \frac{\partial C}{\partial t}.$$  \hspace{1cm} (8)

The second term in equation (8) can be simplified as $V_\text{dc} \frac{\partial C}{\partial x} \frac{\partial x}{\partial t} = \eta \frac{\partial x}{\partial t}$. Therefore, total current is

$$i \approx C_0 \frac{\partial V_\text{ac}}{\partial t} + \eta \frac{\partial x}{\partial t}. \hspace{1cm} (9)$$

The first part of equation (9) is the current through a static capacitor and second term is the current due to the motion.

An equivalent electrical model for a resonant transducer with electrostatic input and output ports is illustrated in Fig.9(b). The transformer at the input port converts an input voltage to a force, $F_{in}$, and applies it to the mechanical structure represented by the series RLC circuit. At the output, another transformer converts velocities of the mechanical structure back to an electric current. In the model, $\eta_\text{in}$ and $\eta_\text{out}$ represent electromechanical coupling coefficients. $C_{\text{pad}}$ is the shunt capacitor usually about 1 pF to 2 pF. $C_0$ is the nominal capacitor given as $C_0 = \frac{eA}{d}$. Other equivalent parameter can be expressed as, $L_m = \frac{m_{\text{eff}}}{\omega^2}$, $C_m = \frac{\omega^2}{k_{\text{eff}}}$, $R_m = \frac{\sqrt{KM}}{\eta n^2}$ and $\eta = \frac{dC}{dx}V_\text{dc}$. Parameters $L_m$, $C_m$, $R_m$ and $\eta$ are equivalent inductance, capacitance, motional resistance and electromechanical coupling factor, respectively. $V_\text{dc}$ is the DC voltage used to polarize a micro-transducer. From the equivalent circuit, a series resonant frequency is derived as

$$\omega_s = \frac{1}{\sqrt{L_m C_m}}, \text{ and } Q = \frac{\omega_m}{\omega_m R_m}.$$  

A mechanical resonant frequency of a transducer can be given as $\omega = \frac{k_{\text{eff}}}{\sqrt{m_{\text{eff}}}}$. When an external perturbation is applied, altering either an effective stiffness, $\Delta k$ or an effective mass $\Delta m$ of a vibrating element, the resonant frequency changes to $\omega_{\text{new}} = \sqrt{\frac{k_{\text{eff}} + \Delta k}{m_{\text{eff}}}}$ or $\omega_{\text{new}} = \sqrt{\frac{k_{\text{eff}}}{m_{\text{eff}} + \Delta m}}$, respectively. The normalized sensitivity of a resonant sensor can be characterized as [131].

$$\left| \frac{\Delta f}{f_1} \frac{\Delta m}{m_{\text{eff}}} \right| = \frac{1}{2}. \hspace{1cm} (10)$$

Equation (10) states that for a given effective mass, $m_{\text{eff}}$ and a resonant frequency, $f_1$, $\Delta m$ can be quantified by measuring the frequency shift, $\Delta f$. Other geometries of MEMS/NEMS resonant transducers (cantilever/tuning-fork/plate/disk/bar/membrane, etc.) are also used due to the advantages, such as relatively high $Q$, higher admittance, etc. [127], [132].
1) Mode-localization in resonant sensing

Single element resonant sensor offer obvious advantages such as simple mechanical design, quasi-digital nature of a signal, and high resolution (up to $10^{10}$ gram scale) [131]. However, disadvantages are they are prone to environmental shifts (pressure and/or temperature), their sensitivity is limited to only 0.5 (equation (10)), and being a single element they can detect only one type of material at a time. To address these issues, in recent years, a novel form of transduction called "mode-localization" is being pursued to enhance the performance of resonant sensors, particularly their parametric sensitivity and common-mode rejection [82] [131]. The mode-localization involves an array of oscillating proof masses coupled either electrostatically or mechanically (Fig. 10(a)). An applied perturbation alters the effective mass ($\Delta m$) or stiffness ($\Delta k$) of one of the proof mass, and vibration energy gets confined (localized) to the small geometric region of this coupled oscillators. The sensitivities of mode-frequencies, $s_k$ and modal amplitude ratios, $s_o$ to an applied perturbation of this coupled oscillatory sensors can be expressed as

$$s_k = \frac{\partial (\omega)}{\partial (\delta_k)} = \left( \frac{\Delta k}{2K_c} \right) \left( \frac{K_{eff}}{\Delta k} \right) = \frac{1}{2} \cdot (11)$$

$$s_o = \frac{\partial (\delta)}{\partial (\delta_o)} = \left( \frac{\Delta k}{2K_c} \right) \left( \frac{K_{eff}}{\Delta k} \right) = \frac{K_{eff}}{2K_c} \cdot (12)$$

Comparing equations (11) and (12), we see that amplitude sensitivity is $K_{eff}/K_c$ times sensitive than the frequency shift output. The mode-localized sensors exhibit ultra-high parametric sensitivity, up to three to four orders of magnitude higher than traditional resonant sensors, and better immunity to environmental parameters such as pressure and temperature [131]. As a result of their higher parametric sensitivities, m-DoF coupled resonators are emerging as a promising alternative to traditional resonant sensing solutions. A finite element simulation of the resonant frequencies and corresponding mode-shapes of the two coupled beams is seen in Fig. 10(b).

F. Optical

MEMS optical sensors can detect various optical parameters, including intensity, wavelength, polarization, and phase, and convert them into proportionate electrical signals. One of the key advantages of MEMS optical sensors is their ability to integrate multiple sensing elements into a single device, enabling the detection of multiple optical parameters simultaneously [133]. This integration can also reduce the complexity and cost of optical sensing systems. MEMS optical sensors are used in air quality monitoring systems to detect and measure particulate matter and other pollutants [133], [134]. They are also used in biomedical applications such as glucose sensing and DNA sequencing [135]. MEMS optical transducers can be used as optical switches, filters, modulators, and sensors, among others [136]. One of the key advantages of MEMS optical transducers is their miniaturization, low power and integration capability, which allows for the development of compact and high-performance devices.

Various types of MEMS optical transducers have been proposed and fabricated, including MEMS-based Fabry-Perot interferometers [137], micro-ring resonators [136], photonic crystal cavities [4], and microcantilevers. These devices rely on the mechanical movement of microstructures to achieve optical modulation or sensing. For example, a MEMS-based Fabry-Perot interferometer consists of two reflecting surfaces separated by a small air gap [138]. By changing the distance between the two reflecting surfaces using MEMS, the interference pattern of the device can be modulated, allowing for optical modulation or sensing. MEMS cantilever-based biosensors utilize the mechanical deflection of a cantilever due to the binding of a biomolecule to its surface. The change in deflection can be detected optically, allowing for label-free detection of the biomolecule [136]. Optical MEMS has become very prevalent because of its high performance (high displacement accuracy) and resistance to electromagnetic interference [135]. Example application is accelerometer using Fabry–Pérot interfere technology [135], optical Fabry–Pérot (FP) pressure sensor for wind pressure measurement [137].

Table I provide a comparative summary of various parameters linked to overall functionality and performance of various transducers we analyzed. It provides a values of the actuation and sensing parameters that could help chose a specific transduction scheme for the device development and specific application.

VIII. Summary and Outlook

The paper precisely covered various transduction principles used in MEMS/NEMS, along with operation, performance and latest applications. An electrostatic transduction offers ultra-low power, faster response and compatibility with electronics integration. However, nonlinearity, pull-in, relatively lower coupling factor, lower input force and resulting lower displacement are its limitation. Electrostatic transducer applications are also limited to MHz range. Internal dielectric transduction uses larger dielectric coefficients (high-k thin films) and improves the electromechanical coupling (transduction efficiency). It also scales to operate devices at ultra-high frequencies (GHz). However, larger parasitic, and electronics integration are few of the challenges with it. Thermal transduction offers relatively larger input stroke and resulting displacement, can integrate with on-chip electronics. Scaling down the dimension of thermal transducers have enabled their operation in MHz region. However, they need larger energy to operate and have larger time constant. Piezoelectric transducer offers enhanced transduction efficiency, linear and direct 2-way transduction and device can operate in the kHz-GHz frequency range. Challenges of
electronics integration of different piezo thin-films to be overcome, however. Capacitive sensing can precisely detect ultra-small motions (\(\mu\)m), and are ultra-low power techniques, easy to be integrated with on-chip silicon CMOS. However, several challenges as outlined in section III are to overcome. Piezo-resistive sensing is one of the simplest, and easily integrated transduction scheme that is combined with variety of actuations, specifically thermal-piezo-resistive and electrostatic. They consume relatively larger energy than capacitive sensing, though. Efforts are ongoing to optimize and enhance transduction efficiency of each of the transducers (actuator and sensor) that leads to higher performance in a given application.

**REFERENCES**


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\[ F_s = Kx \quad F_c = C\dot{x} \]

**Mechanical**

- Force, \( F \)
- Velocity, \( \dot{x} \)
- Motion, \( x \)
- Spring, \( l/k \)
- Mass, \( M \)
- Damping, \( \zeta \)

**Electrical**

- Voltage, \( V \)
- Current, \( I \)
- Charge, \( q \)
- Capacitance, \( C \)
- Inductance, \( L \)
- Resistance, \( R \)

**Fig. 1.** A solid-state model of a MEMS/NEMS transducer (a), cross-domain mapping example, (b).
Fig. 2. Parallel plate actuator featuring electrostatic actuation: out-of-plane, gap modulated transducer (a), and in-plane, gap/area modulated transducer (b).
Fig. 3. Schematic showing principle of dielectric transduction, (a), modified parallel-plate transducer for internal dielectric transduction by filling the air-gaps, (b) and schematic representing bulk, longitudinal mode transducer with high-k dielectric thin films (c)
Fig. 4. Two variants of an electro-thermally actuated transducers: in-plane, uni-material (a) and out-of-plane, bi-material (b). Motion sensing can be accomplished via capacitive and/or piezo-resistive mode.
Fig. 5. A basic model of an electromagnetic transducer. A movement caused by the generated Lorentz force can be sensed via capacitive and/or piezo-resistive scheme.
Fig. 6. Various configuration of a piezoelectric transducer, fixed-fixed beam (a), cantilever (b), surface acoustic wave (SAW) (c), and membrane (d).
Fig. 7. A piezo-resistive sensing scheme with cantilever and membrane based structure (a), and a signal conditioning Wheatstone bridge to convert resistive changes into proportionate voltage difference output (b).
Fig. 8. A schematic representation of thermocouple to be used in a MEMS-based thermoelectric IR sensor: An output voltage, $V$, is generated when an IR radiations incident on the sensor, $V = (\alpha_A - \alpha_B)\Delta T$, where, $\alpha_A$ and $\alpha_B$ are Seebeck coefficients of material and $\Delta T$ is the temperature difference between measurement and ref. junction (a). 3D view of a microbolometer pixel. An array of such pixels (e.g. 640×480) are used to construct a microbolometer chip (b).
Fig. 9. A vibrating mechanical resonant beam transducer (a) and an equivalent electrical circuit model of a resonant transducer, (b)
Fig. 10. Schematic of an array of resonating transducers used as mode-localized sensors (a), mode-shapes of a two coupled beam sensors, (b)
### TABLE I
**Comparison Amongst Commonly Used MEMS/NEMS Transduction Techniques**

<table>
<thead>
<tr>
<th>Transducer</th>
<th>Force</th>
<th>Respons</th>
<th>Force magnitude</th>
<th>Displacement</th>
<th>Drive voltage/current</th>
<th>Power/current</th>
<th>Frequency</th>
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<td>PiezoMUMP s) by MEMSCAP</td>
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\[ F_{el} \approx \frac{d_{31}}{d_{33}} V^2 \]

\[ F_{th} = \frac{\alpha_T A E}{T - T_0} \]

\[ F_{em} = q \vec{v} \times \vec{B} \]

\[ F = e_{31} W V = E_p d_{31} W V \]
Transductions in MEMS/NEMS

Capacitive

\[ C = \frac{\varepsilon A}{d} \]

Piezoelectric

\[ F = B i L \times \sin \theta \]

Thermal

\[ \frac{C}{C_0} = \frac{\varepsilon A}{d - x} \]

Piezo-resistive

Piezoresistive

Magnetic

Infrared flux