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REVIEW ARTICLE

Micro-cantilever sensor principle, design, fabrication and application: A review

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ABSTRACT - Micro-cantilever sensors have emerged as a transformative technology in the fields of physical, chemical, and biological sensing. Their ability to detect minute forces and changes at the nanoscale makes them ideal for applications that demand high sensitivity and portability. While these sensors have gained prominence across various domains, including medical diagnostics, environmental monitoring, and industrial testing, the field faces ongoing challenges related to their fabrication, sensitivity, and integration. This review provides a comprehensive overview of micro-cantilever sensor technology, focusing on advancements in their operating principles, design, fabrication methods, and diverse applications. Despite their many advantages, including low cost, portability, and high sensitivity, micro-cantilever sensors are still limited by issues such as fabrication difficulties, reliability, and scalability. This work aims to address these challenges by examining current trends, identifying gaps in the literature, and proposing potential solutions for overcoming the technical barriers. Key areas covered include the development of novel materials, fabrication techniques, and sensor integration methods, with a particular focus on their applications in healthcare, food safety, environmental monitoring, and explosive detection. Furthermore, the review explores the future potential of micro-cantilever sensors in emerging fields such as point-of-care diagnostics and personalized medicine. By consolidating existing knowledge and identifying areas for further research, this review highlights the importance of advancing micro-cantilever technology to enable new applications and improve existing ones. Ultimately, this work aims to contribute to the development of more reliable, scalable, and versatile sensing devices, thus expanding the potential for micro-cantilever sensors to impact a wide range of industries and applications.

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1. INTRODUCTION

The cantilever-based sensing research was geared up from the beginning of 1991 and rapid research is observed afterwards in this field of research [1]. These sensors allow the measurements of the quantities and phenomena which are quite difficult to be measured by the other methods. The sensors are versatile and can be operated in a variety of modes which can yield different information. Further, the information can be combined to obtain a useful set of coupled data. Many of the review works of literature have presented the cantilever sensing technique and compared it with the other sensing techniques [1–8]. Qavi et al. [1] reviewed label-free technologies for quantitative multiparameter biological analysis, emphasizing their applications and advancements in biosensing techniques. Fritz [2] discussed the principles and applications of cantilever biosensors, highlighting their sensitivity and versatility in detecting molecular interactions. Singamaneni et al. [3] introduced bimaterial microcantilevers as a hybrid sensing platform, demonstrating their potential in highly sensitive detection systems. Waggoner and Craighead [4] reviewed micro- and nanomechanical sensors for environmental, chemical, and biological detection, focusing on their operational principles and applications. Carrascosa et al. [5] highlighted the emergence of nanomechanical biosensors as innovative tools for sensitive and specific biological sensing. Boisen and Thundat [6] described the design and fabrication of cantilever array biosensors, emphasizing their multiplexing capabilities and fabrication challenges. Hwang et al. [6, 7] presented an overview of micro- and nanocantilever devices for biomolecule detection, detailing recent advancements and applications. Binnig et al. [8] introduced the atomic force microscope, a groundbreaking technology that laid the foundation for nanoscale sensing and imaging.

The micro-cantilever devices can be employed for sensing purposes in various fields including physical, chemical and biological. Some other applications of these devices are screening of diseases, detection of point mutation, blood glucose monitoring and detection of chemical and biological warfare agents [9, 10]. These micro-devices possess many advantages over conventional techniques such as high sensitivity, less cost, simple procedure and quick response [11]. The miniaturization of technological devices is essential for their more effective sensitivity and easier portability. The conventional sensing devices required huge packaging, complex electronic interfacial devices and frequent maintenance of them. Therefore these all hitches can be minimised with the utilization of micro and nanodevices which exploits micro-

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electromechanical system (MEMS) technology for the integration of electronics and micromechanical structure on chips [11].

Micromanipulation and micro-assembly have attracted great attention in the past twenty years. MEMSpossess various advantages such as lesser power requirement, higher performance and easier mass-production as well, which makes them suitable for micro-robotics devices and smart portable devices [12, 13]. The research work in the field of MEMS devices was triggered by Richard Feynman at the American Physical Society at the California Institute of Technology [11]. In the beginning of the 20th Century, many technologies have been developed for the fabrication and use of nano-cantilevers for sensing purposeswhich has given the rise to the nano-electro-mechanical system (NEMS). NEMS technology has grown the sensitivity limit up to the extent that the visualization of counting the molecules can be done [11]. The minimizing size of the technological devices has made the molecular diagnostic devices smaller in their size more and more. This trend has accelerated the interest of researchers in the field of bio-sensing devices on the miniaturizing platform [11]. Tom Albrecht from Stanford University [14] and the group of Wolter from International Business Machines Corporation [15] first invented the micro-machined cantilever with integrated tips in 1990. Further, Thomas Thundat and his co-workers [16] explored the cantilever to be utilized as a physical and chemical sensing instrument. A microcantilever sensor acts as a physical, chemical and biological sensor by detecting the changes in its vibrational frequency or deflection. The mass added or molecules adsorbed on a micro-cantilever cause its vibrational frequency or deflection changes.

An efficient and secure gripping to handle the micro objects requires a micromanipulation system with the force sensing capability at the micro-scale [17]. The macro-force sensing instruments are well developed in the present time but these instruments are not suitable for the measurement of micro-magnitude of forces. The people are usually unable to feel the force while using the tool to operate the micro objects like tiny blood vessels. The sense of touch and the capability to sense the micro-magnitude of forces in such type of application is required to improve the results and safety [18]. On the other hand, the micro-objects and micro-tools for their handling are very much susceptible to being destroyed by the excessive magnitude of force, so these forces sensing is more important. Several factors affect the micro gripping forces such as the contact material and surfaces and the operational condition and procedure. Therefore any experimental and analytical model is almost impossible and can make accurate predictions [19]. The invention of the atomic force microscope (AFM) made the micro-sized cantilever available [8]. Generally, AFM works as a phonograph, where the images are obtained by raster scanning with the help of an AFM probe. The cantilevers with the integrated readout come in to picture in the 1990s. Nowadays many researchers around the world are investigating various readout methods for cantilever sensing devices. The realistic application and utilization of micro-contact force sensors is the attention-dragging object of the current researcher [8]. This presented review emphasises the development of the MEMS cantilever sensing devices, their working principles, operational modes, fabrication process and diverse application fields. The basic structure of this review is shown in Figure 1.

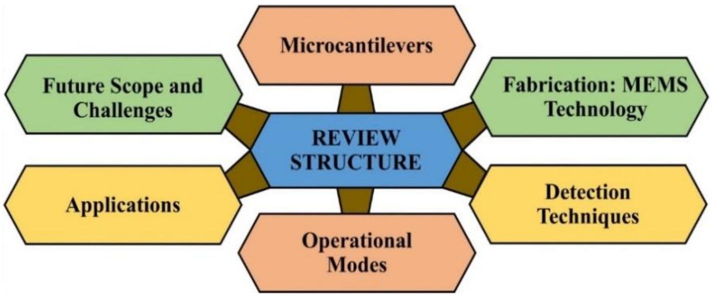
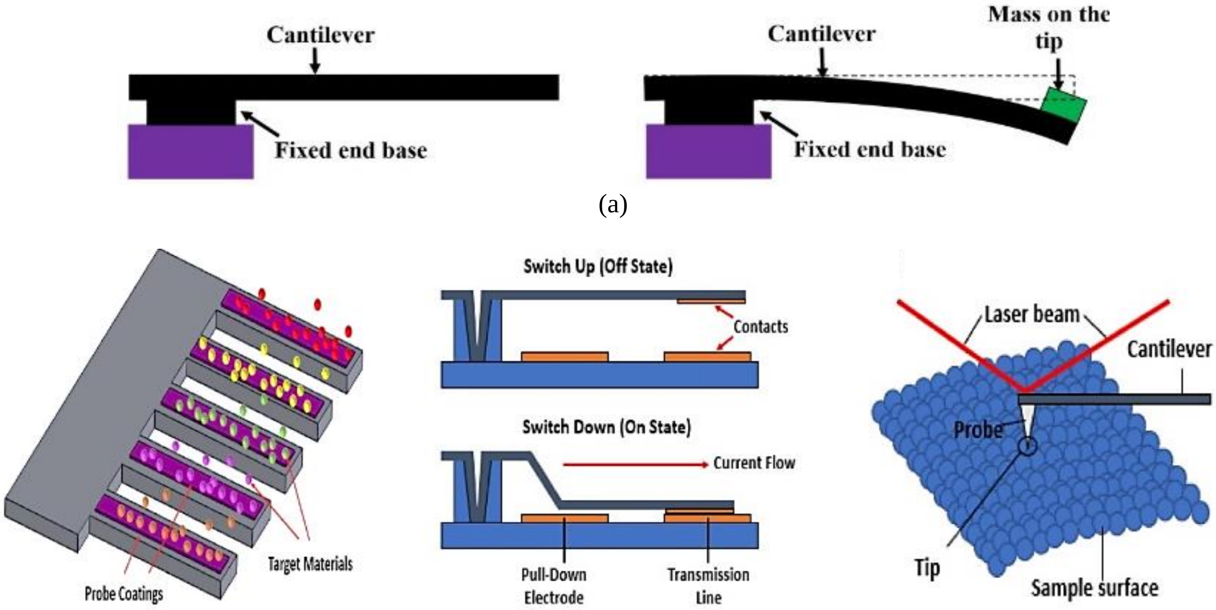


Figure 1. Review structure

This review aims to provide an overview of the diverse field of cantilever-based detections. In section 2 the basic introduction to micro-cantilever sensors is given. Section 3 of the review provides an introduction to the MEMS technology followed by the material and fabrication method of cantilever sensing devices and their sensitivity improvement. Section 4 contains the various detection techniques and modes of operation of the microcantilever sensors. The applications of the microcantilever sensors are enlightened in section 5. The review ends up with a general explanation of the future scope and challenges of the cantilever sensors in section 6.

2. MICRO-CANTILEVER SENSOR

The mechanical beam structure fixed at one end and free at the other is called a cantilever and when the dimensions of this beam are in the range of microns, it is called a micro-cantilever. Micro-cantilevers can have a length of a few microns to several hundred microns and a thickness of a few nanometers [20]. For the miniature dimensions of the structure, the length-to-area and area-to-volume ratio tends to change drastically and these changes alter the relative effects of different physical parameter considerably [21]. Thus basically microcantilevers are miniature leaf connected at one end to support and the other free end is subjected to some external stimulus such as mass, force, stress, heat, viscosity etc. These stimuli cause the deflection of the microstructure or change its resonant frequency. The cantilever sensor and its basic working principle areshown in Figure 2(a), in which the mass on the tip of the cantilever caused it to deflect or change its natural vibrational frequency.



(b) (c) (d)

Figure 2. Micro-cantilevers: (a) mass sensor, (b) chemical sensor array and (c) MEMS switch, (d) AFM cantilever [18]

Micro-cantilevers are the MEMS structures which are used for sensing, actuating and acting as a test device in different micro-system [22, 23]. These micro-cantilever sensors have now become the centre of attention for the researcher as they can be used as a basis for the development of various novel physical, chemical and biological devices [22–24]. They have a huge potential to be utilized as a sensor in different application domains like physical, chemical, biological and biomedical. The MEMS-based micro-cantilever play has vast applications in sensors, actuators, frequency switches, filters, probes, resonators and transduces devices. AFM utilized micro-cantilevers as a testing probe. Micro cantilevers are also used as sensors forthe optical lever read-out scheme. The micro-cantilevers also works as actuator and controller in many devices for the movements in order of microns. Figures 2(b-d) showed the different applications of microcantilevers. These micro-cantilever devices have the advantages of quick and real-time response, low power consumption, high sensitivity and easy bulk fabrication [20].

3. MEMS TECHNOLOGY AND MICRO-CANTILEVER FABRICATION

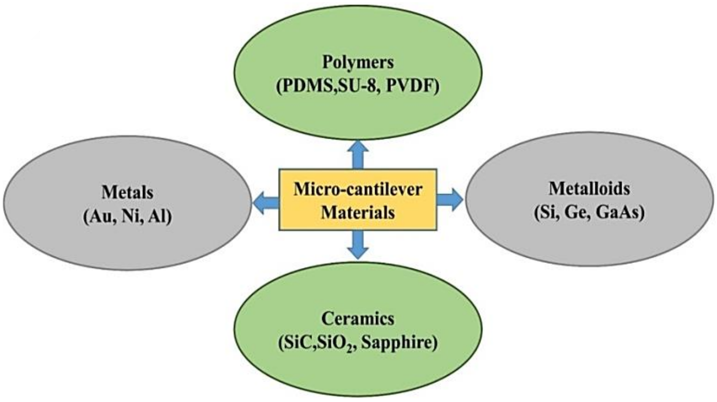
3.1 MEMS Technology

MEMS is defined as the combination of electrical and mechanical systems together to fabricate a micro-sized system. MEMS are generally micro-structures incorporated into the silicon substrate that combines the mechanical element with the electronics and thus, as a whole, it unites the sensing, processing and actuating function together. The microfabrication techniques can also be employed to fabricate multifarious electrical, mechanical, thermal, magnetic, optical and fluidic devices and systems of miniature size [23]. As MEMS includes microscopic dimensions, various coupling effect between different physical domain comes into the picture and the forces which are trifling at the macro-scale need to be considered into account. In the MEMS application, while working with the microdomain, the atomic and surface forces are of more importance compared to the inertial and gravitational forces [23, 25, 26]. These considerations make the MEMS special, as it requires inputs from a different physical domains such as mechanical, electrical, biomedical and biotechnology etc. MEMS also includes intelligent sensors, actuators, signal processors and the communication system as well, on a single substrate [23, 25, 27]. Thus, in short, microtechnology is the study, development and utilization of materials, devices and systems in the range of microns dimensions. This MEMS technology has great potential to develop the next generation of electronic products. Also, the features of MEMS include cost reduction, size and weight reduction, enhanced sensitivity, and cutback in power consumption for integral sensors, actuators and other electronic circuits [26, 27]. Micro-cantilever-based MEMS are proposed to explore the new potential of investigation and to inspire the existing technologies of MEMS. In recent years, the micromechanical cantilever sensor has emerged as an advantageous sensing device compared to conventional sensing systems [26].

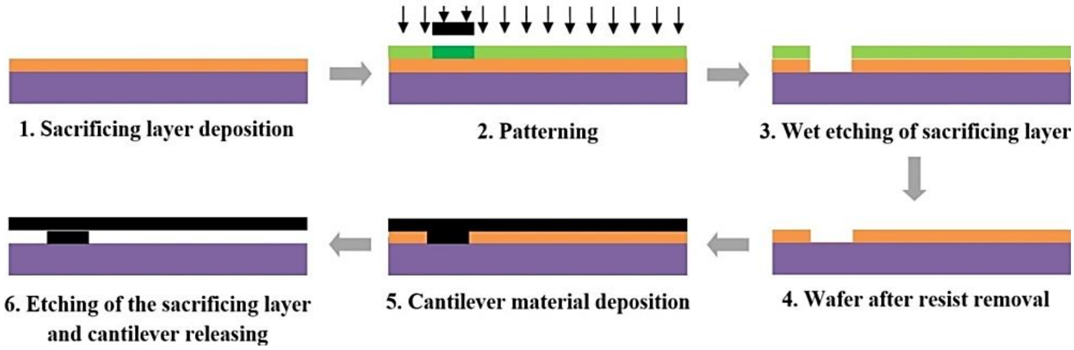
3.2 Materials and Fabrication

The material of cantilever sensors should possess low (average) stiffness or elastic modulus with low density to provide it with sufficient resonant frequency with sufficient deflection abilities [28]. These are the requirements for the better sensitivity of a particular cantilever sensor. Also, the material loss factor should be minimum (low material damping). At presentmany polymer, ceramic, metallic and metalloid materials are available which can be used for the fabrication of the cantilever sensors. The most commonly used materials are Polydimethylsiloxane (PDMS), SU-8, Polyvinylidene fluoride (PVDF), silicon (Si), germanium (Ge), silicon carbide (SiC), silicon dioxide (SiO_2), silicon nitride

(SiN), gold (Au), aluminium (Au), and Nickel (Ni) etc [28]. Cantilever sensors fabricated with these materials are being used in the various application of cutting-edge technology.Different categories of material used for the micro-cantilevers fabrication are shown in Figure 3(a).



(a)



(b)

Figure 3. (a) Micro-cantilever materials and (b) fabrication process

During the literature survey, it is noticed that silicon-based ceramic materials such as silicon nitride and silicon dioxide and sapphire are mostly used for the fabrication of the cantilever sensor. The reason for the use of silicon is its relatively low energy dissipation [29] and high-quality factor [30] compared to the other existing materials (polymers, metals and metalloids). Silicon-based materials are also suitable for nano and micro-scale sensor fabrication through the semiconductor fabrication process such as lithography. Silicon-based materials provide both excitation and measuring facilitiesfor the resonance of cantilevers, through their piezoelectric and magneto-elastic properties [31–33]. For instance, Shih et al. [31] highlighted the use of nanocoating techniques in colloidal processing to enhance the performance of piezoelectric sensors, which leverage the piezoelectric properties of silicon-based systems for increased sensitivity. Lee et al. [32] demonstrated that functionalized $Pb(Zr_{0.52}Ti_{0.48})O_3$ thin-film microcantilevers, which utilize piezoelectric effects, exhibit resonance frequency shifts in response to changes in mass and stress, enabling precise detection of biomarkers like C-reactive protein. Additionally, Li et al. [33] showcased the use of magnetostrictive micro- and millimeter-scale cantilevers, which exploit magneto-elastic properties, as effective biosensors for chemical and biological detection. These studies collectively underscore the critical role of silicon-based materials in advancing resonant cantilever technologies. In the initial developing stage of micro-cantilevers, Wilfinger et al. [34] used silicon for the fabrication of a mesoscale cantilever sensor. A cantilever-type device was also fabricated using a silicon wafer by Petersen [35] to set a connection between silicon transistors and mechanical electromagnetic relays. He also showed that the single crystalline silicon possesses admirable mechanical as well as electrical properties for micro-cantilevers fabrication. Silicon-based sensors are also used in mass sensors to approximate the mass of a single cell [28, 36–38]. The microcantilever fabricated with SiO_2 was utilized as a microsensor by Tang et al. [39], and it was found that SiO_2 based micro-cantilever was approximately 50 % lesser stiff compared to the Si-based micro-cantilever. Cleveland et al. [40] utilized silicon nitride for the fabrication of a micro-cantilever used in the scanning force microscope (SFM). Silicon nitride micro-cantilevers with gold coating were also used in piezo-response microscopy [41]. The zinc oxide layer of high resistivity and piezoelectricity was used to sputter over the microcantilever of SFM by Itoh et al. [42]. The sapphire substrate was used by Heng [43] for the fabrication of the micro-cantilever and he capacitively coupled the fabricated micro-cantilever with the micro-strip lines to achieve high mechanical stability. Piezoelectric material-based cantilever sensors are found to be used for the measurement of the bacterial pathogen concentration in the liquid [39, 44–47].

Polymer base materials such as polysilicon, SU-8, Polymethyl Methacrylate, PVDF and PDMS are also trending for micro-cantilever fabrication. The polymer can be proven a good replacement for silicon but it, on other hand, has temperature constraints as it is a temperature-sensitive material.Many of the polymer materials, possessing comparable elastic properties to the traditional materials, are also investigated with time progress [48–50]. McFarland et al. [48]

demonstrated the production and characterization of polymer microcantilevers, highlighting their potential as an alternative to traditional materials for sensitive and reliable measurements. Further advancements by McFarland and colleagues involved the injection molding of high-aspect-ratio, micron-scale polymeric microcantilevers, showcasing the feasibility of fabricating these structures with precision and scalability [49]. Additionally, their work on micromolded plastic microcantilevers revealed their efficacy in chemical sensing, providing a lightweight and cost-effective solution for various sensing applications [50]. These studies collectively emphasize the growing importance of polymers in enhancing the versatility of microcantilever systems. Polymer-based micro-cantilevers are found cheaper and highly sensitive compared to the common silicon micro-cantilever because of the lower stiffness of polymers [51]. Polysilicon base along with the Au/Cr thin film was used for the fabrication of the bio-MEMS cantilever sensor by Rotake et al. [52]. Kale et al. [53] also developed the micro-cantilever sensor for bio-MEMS application. The micro-cantilever sensor developed by them was made of SU-8-Poly-SU-8 and SU-8-Gold-SU-8 combinations.

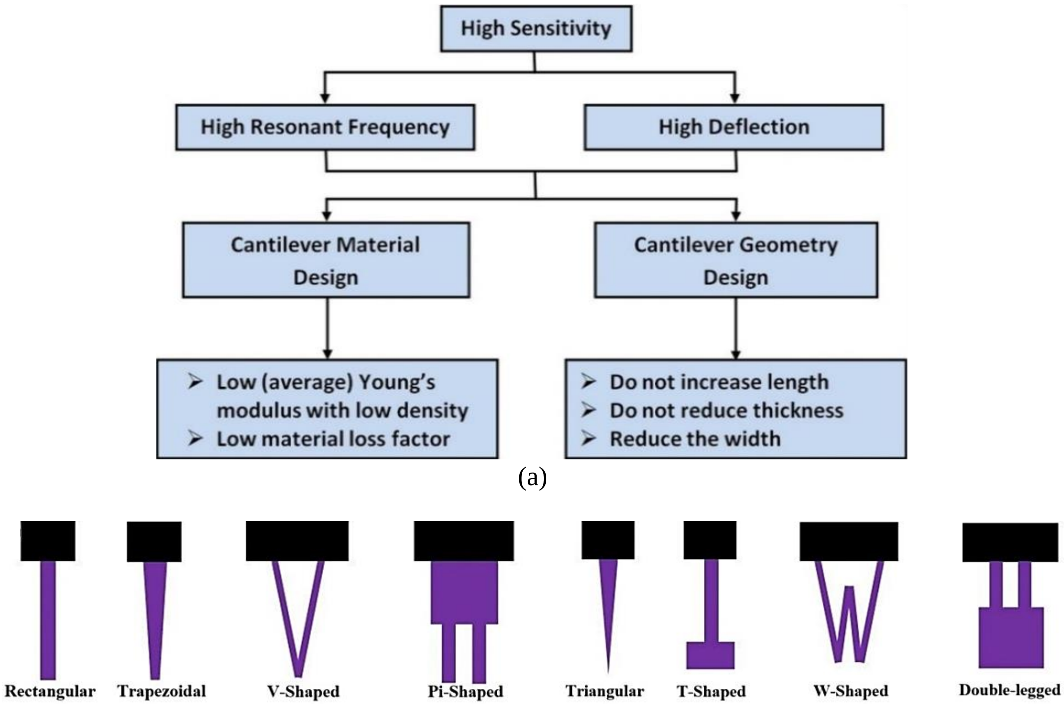
For the sensitivity enhancement of the microcantilever, a metallic/metalloid/non-metallic layer can be deposited over its surface. The cantilevers fabricated with metal oxide are also found to detect prostate cancer biomarkers [54]. The stiffness of gold structured micro-cantilever fabricated by Birleanu et al. [55] was found quite closer to the micro-cantilever of SiO_2 [39]. The metallic-coated silicon microcantilever was used in SFM by Thundat et al. [16], in which they found that gold coating over the silicon microcantilever was useful for better performance. Thundat et al. [56] also used gelatine coating over the micro-cantilever, which was utilized in vapour detection.The composite of SiO_2-Al-SiO_2 was used by Duffy et al. [57] for the micro-cantilever fabrication used in the micro-switch. Multiferroic materials are the potential replacement of lead zirconate titanate (PZT) used for the micro-cantilever fabrication because the multiferroic material have magnetoelectric nature and they can respond through their deflection in both the magnetic and electric field [58, 59]. Many of the micro-cantilever fabrication processes and technologies are described inthe literature [60–62]. Some other techniques like photolithography, laser machining, micro milling operation [63] and plasma etching process [64] are being used for the fabrication of the microcantilever. The plasma-enhanced chemical vapour deposition (PECVD) technique was used for the fabrication of a cantilever bimorph temperature sensor by Melbsurne et al.,in which they deposited polystyrene film on a silicon cantilever substrate [65]. Lin et al. [66] also fabricated a bimorph microcantilever by coating a CNT composite over an Au/Si3N4 cantilever. A functional microcantilever for bio-sensing applications was fabricated by Stassi et al. [67] by using a 3D polymeric printing technology. Kikuchi et al. [68] used the plasma treatment of Nafion for the fabrication of a miniaturized gold-plated electroactivepolymer sensor. Maziz et al. [69] fabricated a polymeric micro-cantilever by producing an interpenetrating polymer network through the reactive ion etching technique. Lei H et al. [70] used the molding method to fabricate an array of Nafion on a substrate base. The electron beam irradiation technique is used by Taaber et al. [71] to fabricate a microcantilever. Shang et al. [72] used a spin coating technique for the fabrication of a polymer/metal bimorph cantilever. A PVC film was spin-coated over a substrate and further some other microfabrication processes such as sputtering were used to obtain the desired coated cantilever sensor. PECVD technique was used by Kim [73] to deposit a nanometer-thick Si3N4 layer over the silicon cantilever which results in an increment of the resonant frequency up to 15.79 %. Prashanthi et al. [52] used pulsed laser deposition and sputtering to deposit nanorods of Dy-modified $BiFeO_3$ and Au/Cr over the Si micro-cantilever. Figure 3(b) shows the process of realizing the typical micro-cantilever through the MEMS fabrication process.

3.3 Sensitivity Improvement

In the literature, various efforts are made for the improvement of the micro-cantilever device sensitivity and linearity. These two are quite important parameters of design. For the sensitivity improvement of the micro-cantilever sensor, the researcherstried to understand the behaviour of the cantilever sensor during sensing operation [74–78]. Fadel et al. [74] investigated the signal-to-noise ratio in resonant microcantilever chemical sensors, analyzing how resonant frequency and quality factor impact sensor performance, thus providing insights into fabrication optimization. Ren and Zhao [77] explored the influence of surface stress on the resonance frequency of microcantilever-based biosensors, emphasizing the importance of precise surface engineering in fabrication processes. Lavrik et al. [75] reviewed cantilever transducers as versatile platforms for chemical and biological sensors, highlighting fabrication techniques that enhance their sensitivity and adaptability for diverse applications. Furthermore, Gibson et al. [76] discussed the calibration of silicon atomic force microscope cantilevers, demonstrating how accurate fabrication processes directly impact measurement reliability and sensor performance. These studies collectively underline the advancements in microcantilever fabrication technologies and their significance in sensor development.

It was found that the sensitivity of a microcantilever is the combination ofthe measurement sensitivity and the design sensitivity [79]. The measurement sensitivity is basically how precisely a sensor can sense the stimulus of interest without including the effect of ambient disturbance in that. The measurement sensitivity of the cantilever sensor can be improved by enhancing its fundamental resonant frequency [79]. The resonant frequency of a cantilever sensor should be high to minimize the effect of vibrations from the surroundings and also to obtain a high image acquisition rate [79]. The measurement is also affected by the signal-to-noise ratio. So, to improve the measuring sensitivity the signal-to-noise ratio should be high, which can be done by making the resonant frequency as high as possible [79]. The correct explanation of the noise in the micromechanical system is also necessary to achieve the required performance of a micro-cantilever sensor.To achieve the fundamentally limited performance of resonating cantilever sensors, it is required to explain the noise present in micromechanical systems. While working with the micro things, we need to consider the random vibration of objects because of their being repeatedly struck from all directions by gas molecules. This type of motion is known as Brownian motion. The thermal noise due to this Brownian motion can be minimized by maximizing the spring constant of the cantilever [79]. This is another reason to keep the resonant frequency higher. Thus, we require a cantilever sensor with a comparatively higher resonant frequency to get a higher measuring sensitivity. On the other hand, if we compare the cantilever of different fundamental resonant frequency, then the cantilever having a higher resonant frequency provide the highfrequency shift on adding the same mass on their tip. The better way to get higher resonant frequency is to decrease mass with the same stiffness in comparison to the increased stiffness with the same mass (or reduced stiffness and reduce mass as well). The reason is that we get a high resonant frequency shift or sensitivity. To reduce the stiffness of the cantilever the increment of its length is not a good choice because the increased length reduces the resonant frequency of the cantilever [80]. Then the thickness and width are the two parameters with which the stiffness can be reduced. Out of these two parameters, the width of the cantilever does not affect its resonant frequency because it is directly proportional to the stiffness and mass of the cantilever and got cancelled out as the resonant frequency depends on the ratio of stiffness and mass. Because of the complex fabrication of micro-cantilevers, the elasticity affects their free and forced responses [80]. The accuracy of the measured stimulus with a micro-cantilever also depends on its elastic properties.

Overall, it can be mentioned clearly that the cantilever sensor should be designed in such a way that it exhibits higher deflection and higher resonant frequency. The cantilever possessing higher deflection abilities providesa good quality factor by providing a sharp dip in the impedance and resonant frequency characteristic curve. On the other hand, the higher resonant frequency of the cantilever providesa high frequency shift on adding stimulus on the tip of the cantilever. So the two perspectives for cantilever design in view of the higher sensitivity of the cantilever sensor are shown in Figure 4(a) [55, 81]. The sensing performance of a micro-cantilever in static mode and dynamic mode of operation generally depends on its bending stiffness and the resonant frequency, respectively [40, 82]. The quality factor is also an important factor to determine the dynamic mode sensitivity of the micro-cantilever sensor [40]. The static mode sensitivity of a micro-cantilever can be increased by decreasing its stiffness, which can be obtained by increasing its length [52, 55, 75]. However, the increased cantilever length is not desirable from the point of view of fabrication. During releasing the microstructure, the increased length increases the change of adhesion of the structure to the substrate [75]. The deflection of a rectangular-shaped cantilever was increased by 75% on cutting out the material from the nearby place of its anchor [83], and this contributed to the static mode sensitivity of the cantilever sensor.



(b)

Figure 4. (a) Sensitivity improvement of micro-cantilever and (b) different shape of the micro-cantilever profile

Many efforts have been reported in the literature for the improvement of the design sensitivity of the cantilevers. In most of the biomedical applications, silicon is used for the fabrication of the microcantilever [29, 30]. But because of the high elastic modulus of the silicon, it exhibits lower deflection for a given value of stress change. The polymer can be proven a good replacement for silicon but it, on other hand, has temperature constraints as it is a temperature-sensitive material. A larger deflection of the cantilever sensor for a given value of surface stress insures the higher design sensitivity of the cantilever [84–86]. This can be done by reducing the stiffness of the cantilever by using softer material for fabrication [87–90]. Ansari et al. [82] compared the deflection and vibration characteristics of rectangular and trapezoidal microcantilever profiles, highlighting how geometric modifications can enhance sensitivity and performance. Villanueva et al. [84] demonstrated the use of crystalline silicon cantilevers with piezoresistive detection, emphasizing their ability to detect biomolecular forces with high precision due to optimized deflection properties. Fernando et al. [85] proposed improved cantilever profiles, showcasing their advantages in achieving enhanced deflection and sensitivity in sensing applications. Khaled et al. [86] provided a detailed analysis of microcantilever deflections, presenting strategies for controlling and augmenting deflection in biosensing systems to achieve superior design sensitivity. These studies collectively underscore the importance of optimizing cantilever deflection characteristics to improve the overall sensitivity and effectiveness of microcantilever sensors. Another way of reducing the bending stiffness is to play with the cantilever's profile because the softer material can be damaged during operation. The rectangular profile of micro-cantilevers is most commonly used in various applications. Further, different profile shapes such as triangular, trapezoidal, V-shaped and T-shaped of micro-cantilevers are optimized by the researchers for sensitivity enhancement [82, 91]. Different shapes of micro-cantilever profiles used by the researchers in the literature are shown in Figure 4(b). Subramanian et al. [91] improved the sensing performance of the micro-cantilever sensor by providing the variation in the width of a V-shaped profile micro-cantilever. They obtained improved resonant frequency of the microcantilever after modification in the profile accordingly. On the other hand, the increment in the length of the micro-cantilever resulted in a decrement in the resonant frequency.The mass sensitivity of a micro-cantilever sensor increases by reducing its dimension. As the dimensions of micro-cantilevers functioning in the resonance mode are lowered, their mass sensitivity increases [92]. The mass sensitivity of the piezo-based cantilever sensor was improved by modifying its profile from rectangular (#R) to step-rectangular (#SR) and step-triangular (#ST) [81]. Figure 5 showed the effect of the cantilever profile on its mass sensitivity, in which the mass sensitivity of the three profiles of the cantilever sensor are compared in vacuum and atmospheric conditions.The frequency response of the rectangular and step-rectangular cantilever profile was also studied in vacuum, air and fluidic media. It was found that the frequency response of the step profile was better from the sensitivity point of view [93]. For the sensitivity enhancement of the microcantilever, sometimes a metallic/metalloid/non-metallic layer can be deposited over its surface. Overall, there must be a compromise between the sensitivity affecting parameters like resonant frequency and bending stiffness according to the application and operation mode. In the dynamic mode of operation, the system with high resonant frequency reflects higher sensitivity. While in the static mode of operation, the good deflection capability of the cantilever sensor contributes to the sensitivity.The selectivity of the active region over the microcantilever surface is also an important parameter for the sensitivity of chemical and biological sensors [91].

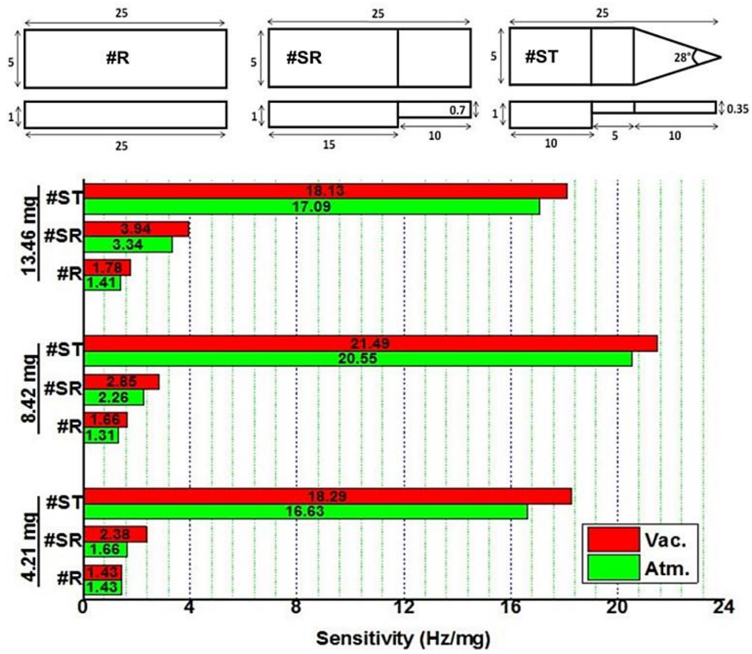
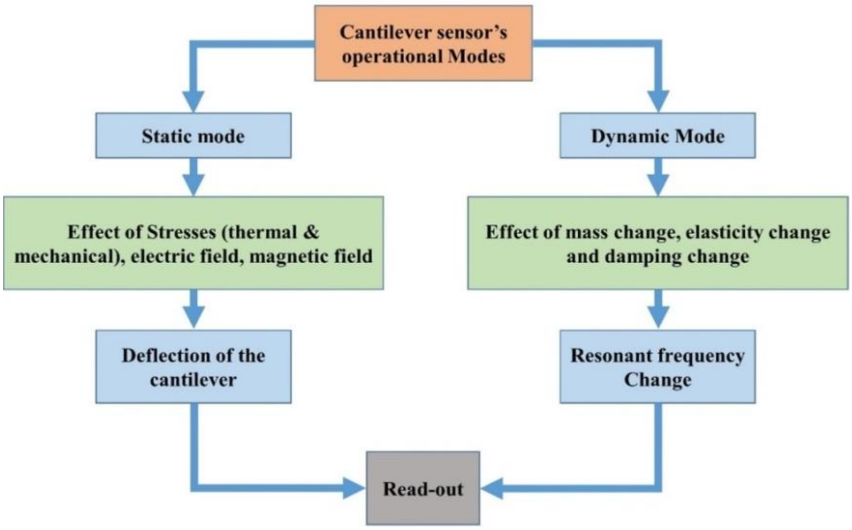


Figure 5. Mass sensitivity of different profiles of cantilever sensor [81]

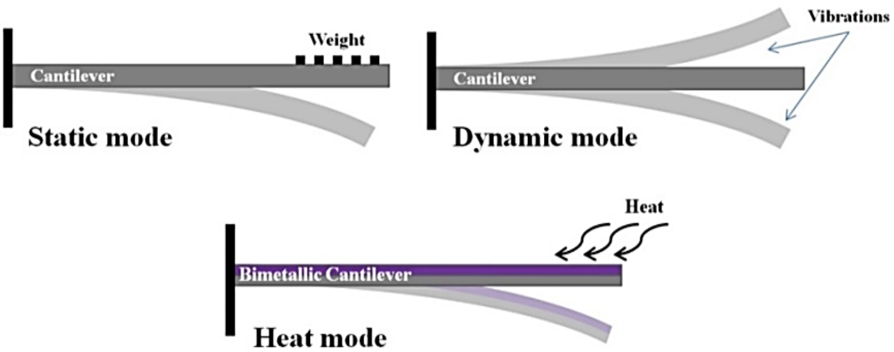
4. OPERATIONAL MODES AND DETECTION TECHNIQUES

4.1 Operational Modes

Basically, two modes are there for the cantilever sensors utilization, named static and dynamic. So the micro-cantilever sensors are operated in either static or dynamic mode. Figure 6(a) shows how the two modes of operation are utilized for stimulus detection. The schematic of the operational modes of the cantilever sensors is given in Figure 6(b). In the static operational mode the measurement of cantilever deflectionbecause of the external stimulus is measured. The external stimulus can be because of any physical, chemical or biological phenomenon. Ibach et al. [94] used the static mode of the cantilever sensor to study the adsorbate-induced surface stress. Berger et al. [95] also used cantilever stress-induced bending caused bythe adsorption of alkanethiols on its surface.The static mode of operation works on binding-induced changes in the cantilever deflection caused by the differential surface stress. Another form of static mode is the heat mode, in which the deflection of the cantilever caused by the heating phenomenon, is measured. Gimzewski et al. [96] presented a calorimeter based on the heat mode. They used the bimetallic effect and the heat produced was measured through the bending of a metal-coated cantilever device.The dynamic mode of operation is based on the cantilever's vibrational motion. Similar to the static mode the external stimulus caused the changein the frequency response of the vibrating cantilever sensor.The sensing in dynamic mode is done by the binding-induced changes in the resonant frequency because of the mass or stiffness change of the cantilever. Dynamic mode of sensing is more suitable for achieving the most sensitive measurements of bio-molecular interactions. Also, in the dynamicmode, the sensing medium is the limiting environment as the vibration of the cantilever can be strongly influenced by damping provided by the environmental fluid [97]. Cleveland et al. [40] used the cantilever sensor in the dynamic mode and the sense mass changes using the resonance frequency shift of the sensor.



(a)



(b)

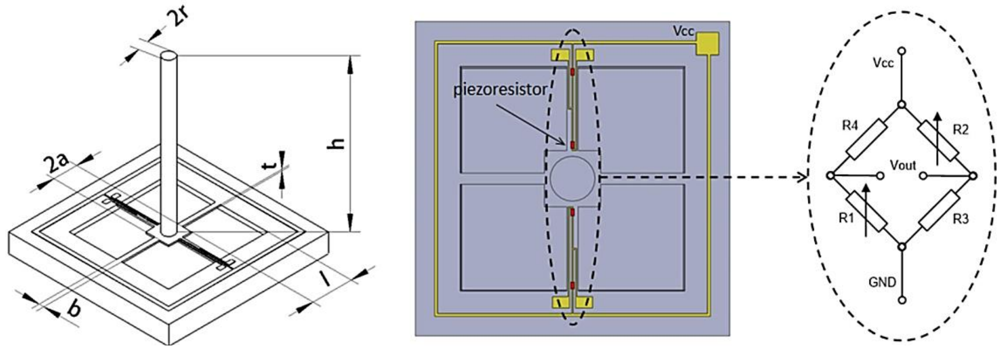
Figure 6. Cantilever operational modes

4.1.1 Static Mode

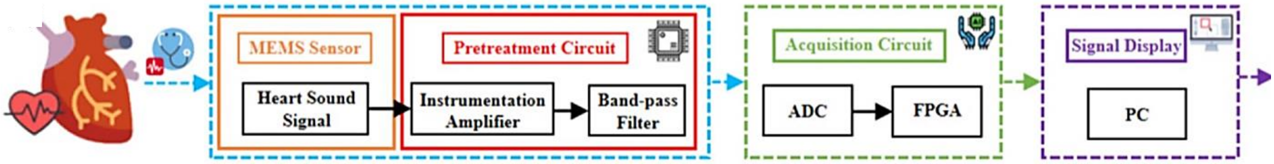
In this mode, the static deflection of the cantilever is measured. The static deflection of the cantilever changes due to physical, chemical and biological reasons. For example, the surface stresses the difference between the two faces of the cantilever and the application of the magnetic, electric and heat field on the sensitive material can cause the deflection of the cantilever, accordingly. The static mode of cantilever operation can also be referred toas the continuous bending of the beam with the increasing mass on its surface [95]. In the case of the functional layer cantilever sensor, the stress is produced at the interface of the functional layer and substance absorbed. The stress produced, tries to bend the cantilever in response. The static mode of operation has been found used in various applications and fast binding of the substances on the functional layer providesa quick response within minutes [95]. This mode is widely used in different biological sensors to detect many biological substances, early detection of many diseases [98] and tissue engineering [99]. The static operational mode was used by Hongfang et al. [100] in an ultra-high sensitive micro-chemo-mechanical hydrogen sensor. The developed cantilever sensor deflected downward after absorbing the hydrogen and the resistance of the circuitry got change because of the cantilever bending. The resistance change indicates the presence and concentration of the hydrogen.

Jiangong et al. [101] developed a heart sound sensor which was based on the static mode of operation. The sensor was designed and processed by MEMS technology and a piezoresistor was implanted in the cantilever beam as shown in the geometry of Figure 7(a). On receiving the heart sound signal, the structure design of the system caused the cantilever deflection. The cantilever deflection was sensed by the Wheatstone bridge and the mechanical deformation was converted intoan electrical signal. Figure 7(b) showed the working system of this sensor operated in the static mode of operation.

Varghees et al. [102] and Chen et al. [103] also utilized the static mode of operation in which they used a similar mechanical deformation to voltage conversion for sensing the heart sound.



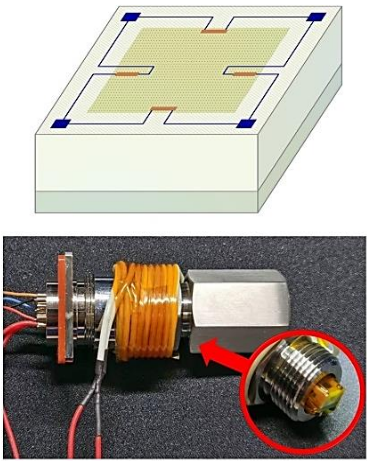
(a)



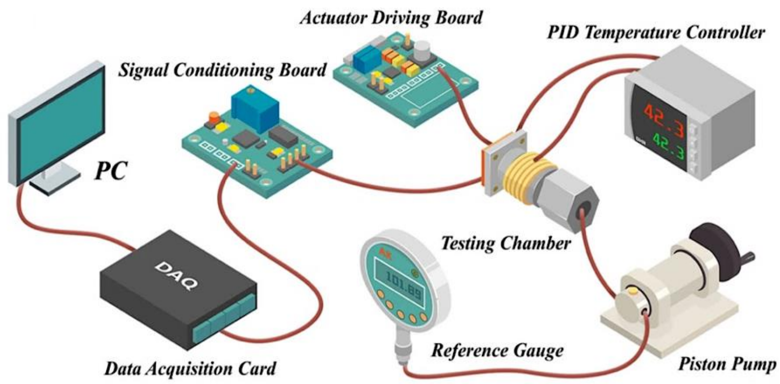
(b)

Figure 7. (a) Sensor microstructure model and piezoresistors on the cantilever with Wheatstone bridge and (b) schematic diagram of the overall test system platform [101]

Generally, the bimetallic effect also comes under the static mode of operation. The two different materials with different thermal expansion coefficients in form of unimorph or bimorph cause the bending of the structure on heating. The amount of bending can be used to sense the stimulus causing the temperature variation. Cheng et al. [104] made a bimetallic actuator-based piezoresistive pressure sensor shown in Figure 8(a), which also worked on the static operational mode. The actuation of the sensor was based on bimetallic thermal expansion, in which the two layers of metal with various expansion coefficients have different degrees of expansion. Further, the pressure sensing was accomplished by the piezoresistive properties of the sensor. The pressure difference between the two sides of the sensor diaphragm made the resistance of the front side piezoresistor increase and the backward side piezoresistor decrease. Thus a differential voltage output can be achieved through the whetstone bridge in response to a pressure change. Figure 8(b) showed the Testing system diagram (TSD) used for the mentioned pressure sensing device.



(a)



(b)

Figure 8. (a) Piezoresistive pressure sensor and testing chamber and (b)Testing system diagram [102, 104]

4.1.2 Dynamic Mode

In the dynamic mode of operation, the frequency response of the sensor is used for stimulus detection. The mass change associated with the cantilever, the stiffness and the damping due to various means, is the main cause, which changes the frequency response of a vibrating cantilever sensor [47, 97, 105]. A variety of different resonant modes can be utilized for sensing purposes. Basically, four modes of cantilever vibration are transverse, torsional, lateral and longitudinal. The fundamental mode shapes of each mode of vibration are shown in Figure 9. The arrows in the figure represent the vibratory motion of the cantilever. The two modes out of the four are lateral and longitudinal modes. These are known as in-planemodes of cantilever vibration. Another two modes of vibration are the transverse and torsional modes of vibration. These are the out-of-plane modes of cantilever vibration. The equation of the motion for all the mentioned modes of vibration can be found in the literature [106, 107]. Each mode of vibration exhibits resonance when the cantilever vibrates with its resonant frequency and it is also known as eigen frequency.

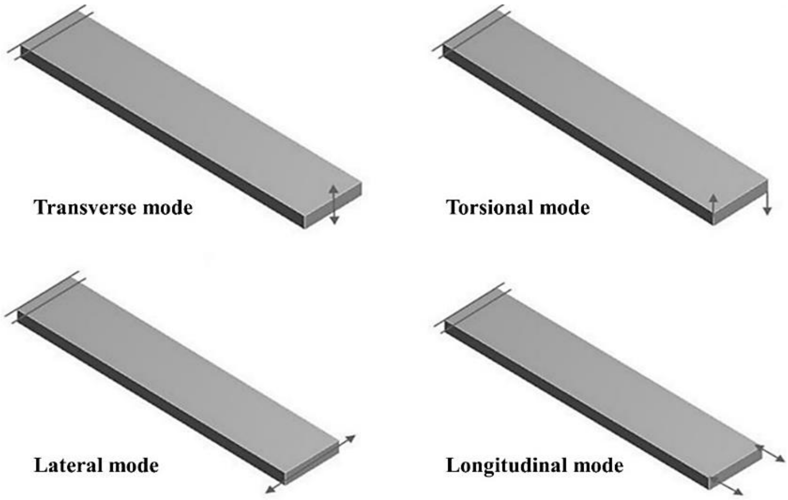


Figure 9. Types of dynamic resonant modes of cantilever sensors

The millimetre-size piezo-based cantilever sensor was used by Shivanku et al. [81] for mass sensing. The operation of the mass sensor was based on the dynamic mode of operation and the resonant frequency change of the sensor was used for the mass change detection. They operated three profiles of the cantilever sensor in dynamic mode and found the resonant frequency of the sensors corresponding to the different masses attached to their profile. The impedance analyser was used for the frequency swapping (Figure 10(a)) and based on the resonant frequency shift the mass change detection was done. The cantilever profile used and their frequency response are given in Figure 10(a) and (b).

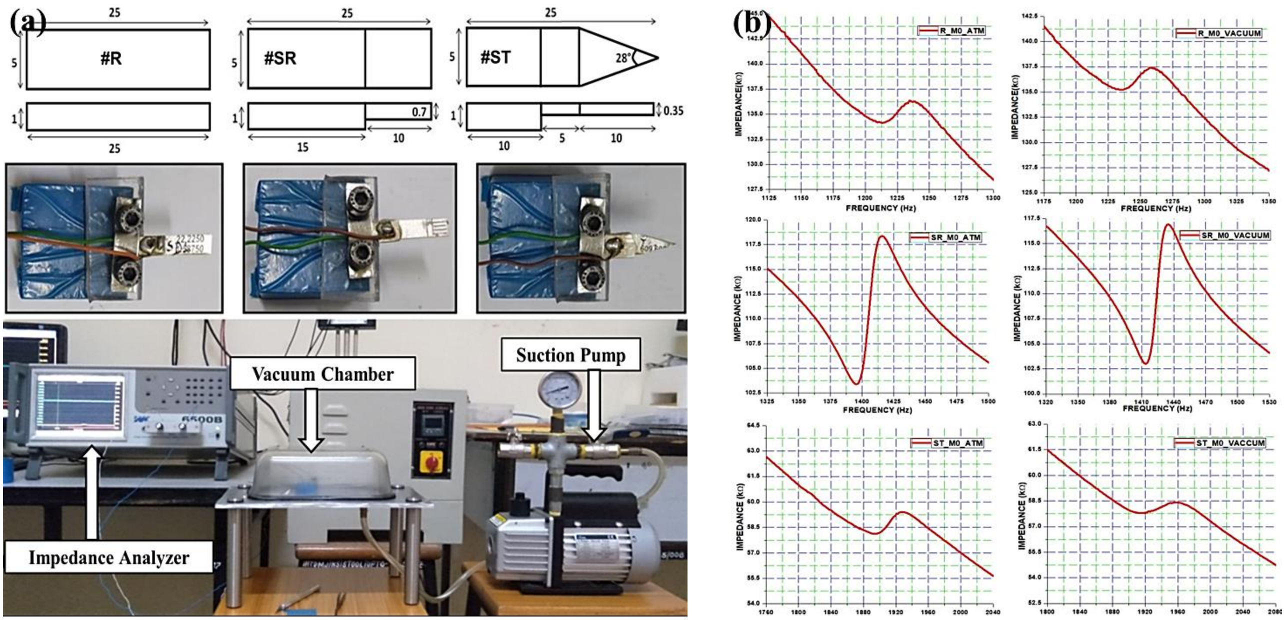


Figure 10. (a) Schematic of different profiles of the cantilever (mm) and experimental set-up for mass sensing and (b) Frequency response of the sensors [81]

Shivanku et al. [93] also used the cantilever device for the fluidic application. The rectangular and stepped rectangular cantilever sensors were used in the resonant mode and their frequency response was used for the media density estimation. The sensors were actuated by the impedance analyser (Figure 11(a)), which also tracks the response of these sensors in the fluidic media. The response of the two sensors in different fluidic media is shown in Figure 11(b).

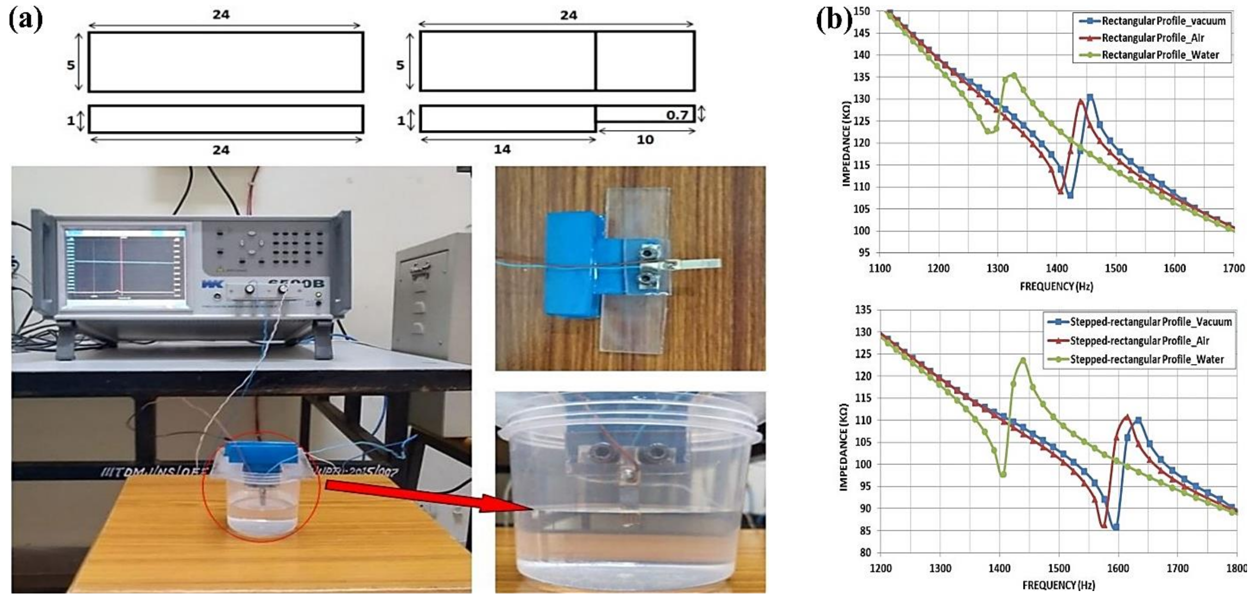


Figure 11. (a) Schematic of the cantilever sensors (mm) and experimental set-up for operation under fluidic media and (b) Frequency response of sensors in different fluidic media [93]

The use of a dynamic mode of operation in the fluidic application is quite effective. The frequency of a rectangular cantilever operated dynamically in a fluidic environment can be given by Eq. (1) as follows [108]:

$$\left[\frac{f_v}{f_m}\right]^2 = 1 + \left(\frac{l}{t}\right).\left(\frac{\rho_m}{\rho_c}\right) g_n \quad (1)$$

where, f_v and f_m are the frequency in vacuum and media, land t are the cantilever length and thickness, ρ_m and ρ_c are the density of the media and cantilever material, and g_n is the fluid mass loading factor on the cantilever.Abdula et al. [109] also used the piezoelectric resonator for underwater applications. Rosmi et al. [110] utilize amicrofluidic cantilever sensor in the dynamic mode for the thermal analysis of liquid analytes.They combined thermal heating with the dynamic mode of operation and monitor the real-time frequency response of the resonator containing liquid analytes. On heating, the analytes with laser-induced radiation, the thermal expansion of the analytes creates thermal stress on the walls of the channel on the cantilever. The thermal stresses caused the rise in the resonant frequency of the cantilever sensor. The frequency shift provided information regarding the fluidic heat capacity, thermal diffusivity and volumetric expansion. Figure 12(a) showed the experimental setup for the operation,in which the laser doppler vibrometer (LDV) continuously tracks the frequency of the cantilever sensor. Figure 12(b) showed the frequency response of the sensor in different fluidic media.

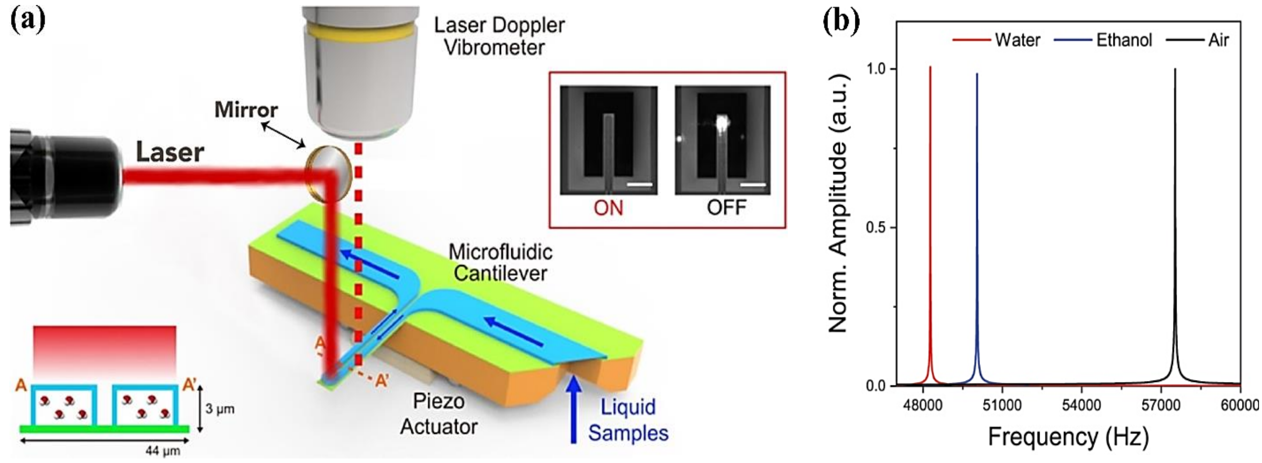


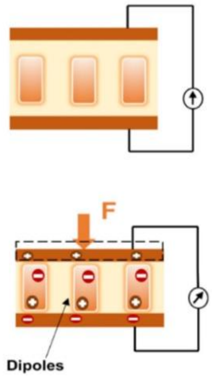
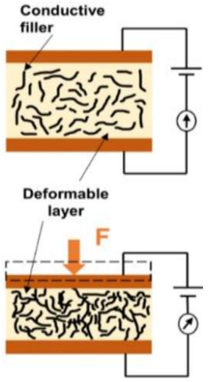
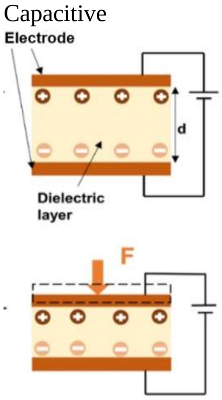
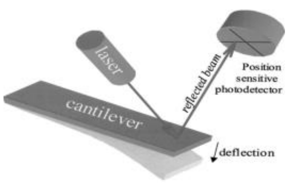
Figure 12. (a) Schematic of the fluidic resonator experimental and (b) Frequency response of the sensor [110]

Dynamic modes of operation have vast applications in mass sensing, gas sensing, fluidics and also in the field of bio-sensing [47]. The ozone gas sensor developed by Amiria et al. [111] was operated in the dynamic mode and the LVD was used for tracking the frequency response. Hu et al. [112] also used the vibrational mode of the PVDF cantilever sensor for the airflow measurement.

4.2 Detection Techniques

The reduced dimensions of the cantilever sensor make it faster, more sensitive and cheaper. Microcantilevers are versatile sensing tools because of their built-in flexibility and monitoring techniques. The cantilever response can be sensed by different read-out techniques or detection techniques such as piezoelectric, piezo-resistive, capacitive, interferometric and optical reflection etc. [5, 51, 105, 113, 114]. Table 1 shows different read-out techniques used in the micro-cantilever sensors.

Table 1. Different read-out methods for cantilever sensing devices

Read-out Methods	Operational principle	Benefits	Detriments	Related References
Piezoelectric  [111]	The differential mechanical stress on the cantilever surface produces an electrical potential across the piezomaterial stacked over it and vice versa.	• This readout method can be employed for sensing as well as actuation purposes • Provide good frequency response.	• Cleanroom incompatibility is one of the problems with most of the piezoelectric material • Some piezomaterials are water soluble and get dissolve in a highly humid environment	[10, 115–122]
Piezoresistive  [111]	The resistance of a piezo-resistive material, attached to the cantilever, changes when the cantilever bends. The deflection of the cantilever can be determined by measuring the change in resistance	• This method can be applied in both liquid and gaseous phases • It can work in all operational modes and facilitate a large array and read-out	• Piezo-resistive layer attached to the cantilever affects its mechanical properties • For the operation in liquid, the resistor needs to be insulated	[90, 123–140]
Capacitive  [111]	The capacitance of the two separated electrodes is changed by the distance change between the two. The deflection of the cantilever also affects the capacitance if placed close to the parallel electrode.	• It can be employed for nano-sized cantilever devices • The mechanical properties of the cantilever are not affected by the read-out method.	• Pre-amplification and CMOS integration are necessarily required • The fabrication process is complicated.	[105, 141–150]
Optical reflection  [67]	The reflected laser light from the mirror-like surface of the cantilever is sensed by a photo-detector.	• Simple procedure • It can be used for any cantilever with good optical quality	• Difficult to apply for large arrays • Not suitable for nano-sized cantilevers and prone to optical artefacts	[10, 151–163]

4.2.1 Piezoelectric Read-Out

Piezoelectricity is a material property which produces electrical charges on the material surfaces when deformed. In the direct piezoelectric effect, the deformation of the material produces an electric charge on the opposite material surface.

Whereas in the converse effect, mechanical deformation is produced when an electric field is applied across the material. The direct effect is used in sensor applications and the converse mode is used in actuator applications [93, 164]. The coupling between the mechanical and electrical domains can be done in the form of a relation between the stress generated in the PZT and its permittivity at constant stress. The strain-charge form during the piezoelectric effect can be given by Eqs. (2) and (3) as follows [164]:

$$S = s.T + d.E \tag{2}$$

$$D = d.T + \varepsilon.E \tag{3}$$

In these Eqs., *S* is the strain, *T* is stress, *E* is the electric field, *D* is electric displacement, *s* is material compliance, *d* is coupling properties and *ε* is the permittivity. For better sensitivity of the sensor in this read-out technique, it is required to operate the cantilever senior in the dynamic mode because the voltage generated by a static force cannot be sustained by the thin layer of piezoelectric material. Thus this technique is generally used with the dynamic mode of operation. The very first time, piezoelectric read-out was used by Itoh et al. [116] in the AFM application. Abula et al. [110] used Aluminum nitride (AlN) piezoelectric material to fabricate the cantilever sensor for underwater application. Zinc oxide (ZnO) and lead zirconate titanate are also promising materials used forthe piezoelectric read-out technique in the sensing application.The piezoelectric read-out method consumes very less power for operation, which is the main advantage of this read-out technique. But, it is quite difficult to work with most of the piezoelectric materials because they are not allowed in the cleanroom and this is the main challenge with these read-out techniques.

4.2.2 Piezoresistive Read-Out

Piezoresistivity is the property that causes the change of electrical resistance of materials because of an applied mechanical load. This property is used as one of the most popular read-out techniques in cantilever sensing devices. The electrical resistance of the piezoresistive sensor changes when the sensor is subjected to mechanical pressure or force [123, 165]. According to Ohm's law, the resistance of any conducting material can be given by Eq. (4) as follows [166]:

$$R = \rho \times (L/A) \tag{4}$$

where, ρ is the resistivity, L is the length and A is the average cross-sectional area of the conductor.

The change in electric resistance on the application of mechanical strain can be given by Eq. (5) as follows [166]:

$$\frac{\Delta R}{R} = (1 + 2\upsilon)\, \varepsilon + (\Delta\rho/\rho) \tag{5}$$

where, υ is the Poisson's ratio, ε is the applied strain and ($\Delta\rho/\rho$) is the resistivity change, respectively. The two terms in Eq. (5) represent the contribution of geometry and resistivity in the total electrical resistance change. The piezoresistive cantilever sensor possesses an integrated resistor in its structure, which has the piezoresistive properties. On the application of the force or pressure the cantilever deflects and this deflection can be determined by measuring the resistance change of the piezoresistor. The piezoresistors are generally based on silicone, metals, metal oxides, carbon-based materials and polymers also. The piezoresistivity read-out method can be employed in micro as well as macro-scale sensors and it has a huge application in flexible sensors [116, 123, 165–167]. The first application of this read-out method in the cantilever AFM device was observed in the research work of Tortonese et al. [129]. The sensing devices based on piezoresistivity are simple in structure and their fabrication is quite easy. This read-out technique can be employed in static as well as dynamic modes of operation.

4.2.3 Capacitive Read-Out

A system of two electrodes separated by a distance or material has its electric capacitance, which changes on changing the distance between the electrode and the facing area of them. The permittivity of the separating material also affects the capacitance of the two electrodes. The capacitance is defined as the change holding capacity, which can be given by Eq. (6) as follows [164]:

$$C = \varepsilon_0 \varepsilon_r A/d \tag{6}$$

where, ε_0 is the free space permittivity, ε_r is the relative permittivity of the separating material, A is the area of the plates and d is the distance between the two electrodes. In the capacitive read-out method, the cantilever sensor deflection is sensed by the capacitance change. Capacitive sensing is most widely used in flexible sensors [168]. The First time the capacitive read-out was used in the AFM application by [141] and later introduced in the sensing application. The capacitance-based sensor can be fabricated with the MEMS technology and the micromachining process but a high degree of process control is required in the operation because the surface quality of the cantilever and counter electrode as well as the distance between them are critical parameters.This read-out technique is highly sensitive and can provide the absolute value of the stimulus. The restriction to the large deflection is the main limitation of this read-out method. Further, the sensors utilizing capacitive read-out, cannot be used in the electrolyte environment as the electrolyte solution may produce faradic current between the electrodes.

4.2.4 Optical Read-Out

The optical read-out technique commonly employed interferometry for sensing purposes. In this technique, a laser beam is focused on the deflected cantilever which acts as a reflector. The interference of a laser beam is reflected from the deflected cantilever and the reference laser beam is used to determine the cantilever deflection. The reflected laser beam reads by the position-sensitive photodetector and gives information regarding the cantilever deflection.This read-out technique is highly sensitive and can provide direct and absolute deflection measurement [163]. The sensitivity of this technique degrades while used in a liquid environment [123]. Amiri et al. [111] used optical read-out through LVD to track the frequency response of their developed ozone gas sensor. Nordstrom et al. [88] used a novel integrated optical readout for the cantilever-based sensor system. The optical read-out technique is most widely used with the microcantilever arrays to track their deflection and vibrational motion. The procedure is quite simple and easy but portability is the problem with this technique. All the mentioned read-out methods, which are used in different kinds of cantilever sensors are described in Table 1, along with their benefits and detriments.

5. APPLICATIONS

Micro-cantilever-based devices have a wide range of applications in the field of physical [169], chemical [154], and biological [5] sensing devices. Micro-cantilevers are also being used in the different MEMS devices, which have been commercialized in the different global markets such as accelerometers, gyroscopes, micro-mirrors, micro-pumps, pressure sensors, micro-fluidics, temperature sensors, micro-heat exchangers, etc . Micro-cantilever sensors can be used to measure the mass, sound wave velocities, fluid pressures, and flow rates and can also detect ultra-violate radiation, gas mixtures, different biological substances, humidity and pH changes etc [170]. Also, the micro-cantilever sensor applications cover diverse fields such as drug discovery, medical and biological detections, food diagnostics, material characterizations, AFM, explosives detection, gas sensing, fluidic sensing, and control systems, etc. [170–172]. Shah et al. [170] explored the modal analysis of a single-structure multi-axis MEMS gyroscope, demonstrating its potential in control systems and precision sensing applications. Giner et al. [171] introduced a MEMS gyroscope with concentrated spring suspensions, showcasing advancements in robust, temperature-stable designs for dynamic sensing and control. Additionally, He et al. [172] proposed structural designs for MEMS capacitive accelerometers, emphasizing their high linearity and low temperature coefficients, making them suitable for diverse sensing applications in challenging environments [173]. These studies highlight the versatility and broad applicability of microcantilever and MEMS-based sensors in addressing complex challenges across multiple disciplines. Different types of sensors based on their application field are explained here in this review.

5.1 Mass and Humidity Sensors

Micro-cantilevers can be effectively utilised in the development of different mass-sensing devices. Shivanku et al. [81] fabricated three piezoelectric-based mass sensors with stainless steel base substrate material. The mass sensitivity of the three sensors is compared in their work and the stepped-triangular profile cantilever sensor was found to have the highest mass sensitivity.The operating condition also affects the mass sensitivity of the sensors and it was found that operating the cantilevers in vacuum increased the resonant frequencies by 1-2 %. Stepped-triangular model of the sensor showed the highest mass sensitivity of about 16.63 Hz/mg in atmospheric and 18.29 Hz/mg in vacuum.

Humidity measurement also plays an important role in different fields like aerospace, petrochemical processing, agricultural production, semiconductor manufacturing, and cargo storage [173]. The deflection and resonant frequency of the cantilever can be altered by changing the mass present on its surface or tip. Based on this fact, any amount of water vapours absorbed on the cantilever surface can be detected easily. For the absorption of the water on the cantilever's surface, many of the hygroscopic substances can be used as a coating. Many humidity sensors have been developed working on different principles and utilizing different hygroscopic materials [174–179]. For instance, $ZnCr_2O_4$-ZnO composites have demonstrated notable humidity-sensing properties due to their effective interaction with water molecules on the material surface [174]. Similarly, nanocomposites like NaPSS/MWNTs have shown promising sensitivity attributed to their unique nanostructures that enhance surface area and facilitate rapid adsorption/desorption of moisture [175]. Zinc oxide-based nanostructures, including nanorods and nanowires, have also been widely explored for their excellent sensing capabilities arising from their high aspect ratio and intrinsic semiconducting properties [176]. Single SnO_2 nanowires have exhibited exceptional sensitivity to humidity changes, making them suitable for applications requiring precise humidity monitoring [177]. Moreover, porous ceramics such as Li-Mg-Ti-O-F materials offer robust humidity-sensitive characteristics due to their tailored porosity and surface chemistry [178, 180]. Recent advances also include the development of inorganic-organic p-n heterojunction nanotree arrays, which provide high sensitivity and fast response times, further expanding the landscape of humidity-sensing technologies [179]. Studies on humidity sensing have progressed swiftly, and these sensors are now employed in industrial applications such as instrumentation equipment as well as in household applications for comfort concerns [173]. The most effective method of humidity measurement is using the dew point (DP) data. The dew point is considered the unit of absolute humidity, and DP determination helps to keep the gas at a temperature that prevents condensation. Wang et al. [181] presented a dew point sensor which can be further utilized to analyse the humidity. The circular and cantilever types of piezoelectric sensors are fabricated and used in this work for dew point estimation. The schematic diagram of the dew point sensor configuration and their SEM images are shown in Figure 13(a). A novel piecewise function fitting dew point identification method is suggested for the measurement. Figure 13(b) showed the system diagram for the dew point measurement experiment. The dew point measurement results of the circular resonator and cantilever sensor are shown in Figure 13(c). This figure also compares the humidity response curves of the two resonators. The output showed that the circular resonator-based sensor has good accuracy with a maximum relative error of the dew point is 0.30 ºC DP, while the cantilever-based sensor showed a maximum relative error of less than ± 0.5 ºC DP.

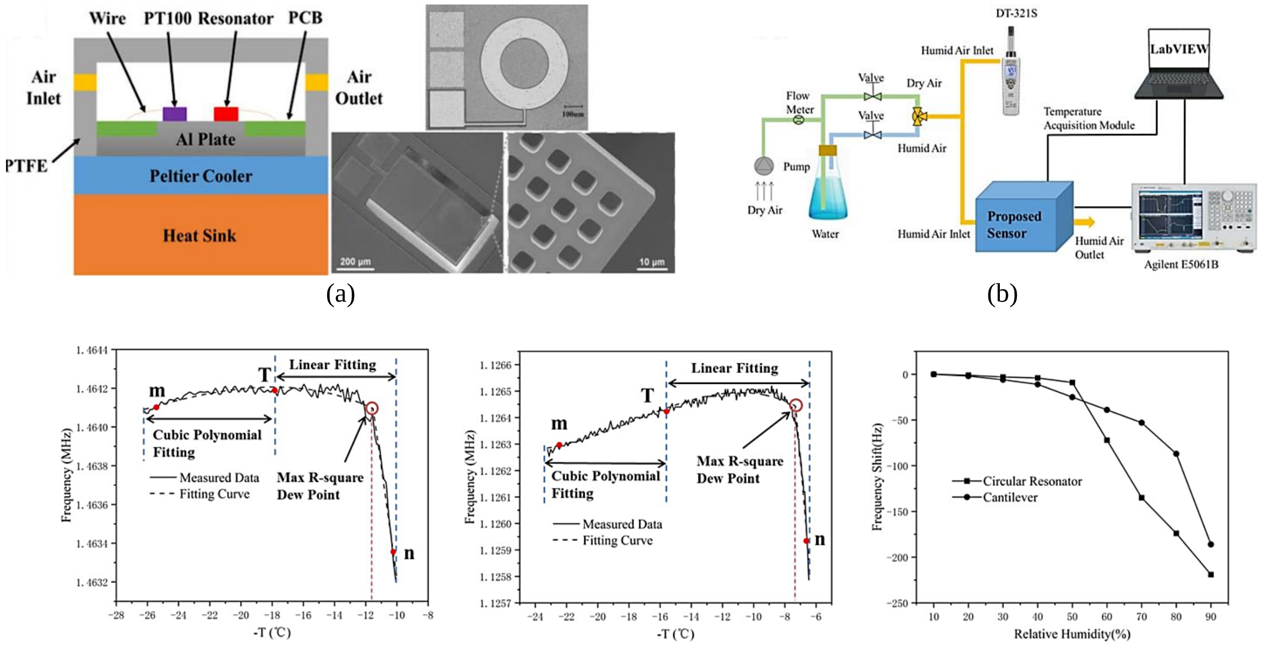
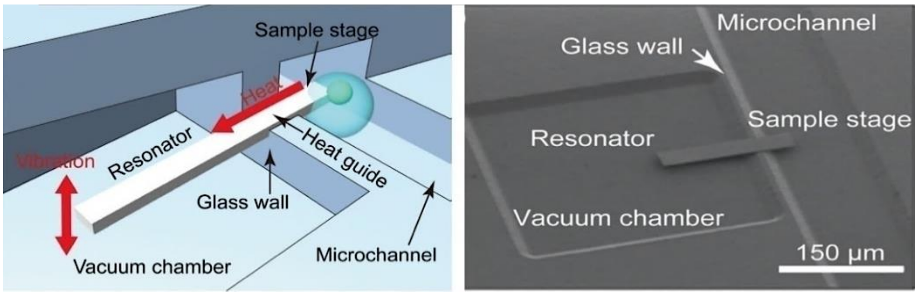


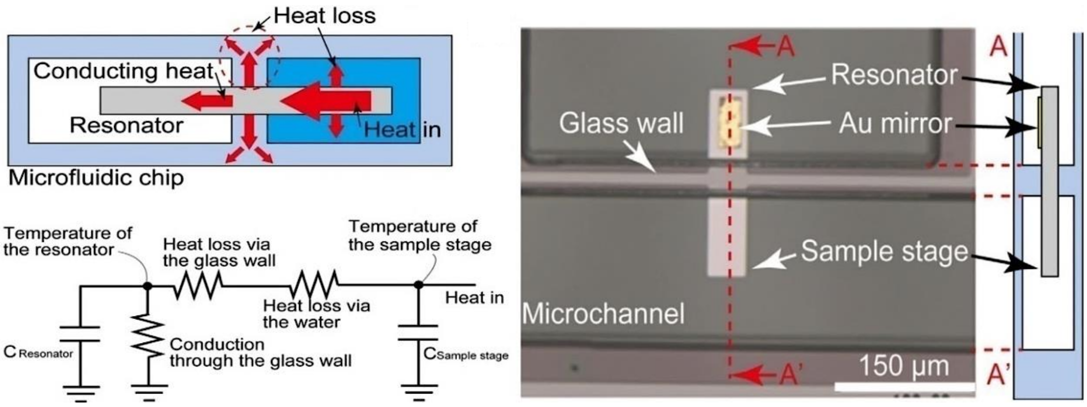
Figure 13. (a) The schematic diagram of the sensor and SEM images, (b) Schematic of the experimental system diagram and (c) Dew point measurement results and humidity response curves of the circular and cantilever resonators [181]

5.2 Temperature and Infrared Radiation Sensors

A cantilever driven in the vibrational mode can be utilized to detect temperature differences [115, 182]. MEMS cantilever structures have been widely recognized as reliable thermo-mechanical sensors for biological and chemical detection, owing to their high sensitivity and versatile functionality [75, 183–186]. Micromechanical cantilevers, for instance, can transduce biochemical interactions into measurable mechanical signals, enabling precise detection of target analytes [183]. The development of cantilever arrays has further expanded their applicability, offering simultaneous multi-analyte detection and increased throughput [184]. Advances in the physics of nanomechanical biosensing have provided deeper insights into the mechanisms governing cantilever behavior, enhancing their performance in detecting biomolecular interactions [185]. Moreover, innovative applications, such as measuring the density of single cells using cantilever-based systems, demonstrate their potential for high-resolution, real-time biological analysis [186]. These advancements underscore the versatility and reliability of MEMS cantilevers in modern sensing technologies. The temperature change is made to relate with the elastic modulus of the cantilever through its vibrational properties. Both, mono-material and bi-material cantilever beams are used for the temperature sensing application. The mono-material cantilever beams are used for the simple calorimeter, and their sensitivity is limited because of their temperature coefficient. On the other hand, a biomaterial cantilever beam calorimeter is fabricated with two thin layers of different materials. The bi-material cantilever is a composite structure having two different constituents of different temperature coefficients. These bi-material cantilevers are highly sensitive to temperature change as they produced deflection of their free end corresponding to even a very small variation in the temperature. The bimetallic cantilever for the temperature sensing calorimeter was first fabricated with a silicon nitride cantilever coated with a thin film of aluminium [187, 188]. Inomata et al. [182] developed a pico calorimeter, which they utilized in detecting the heat from a biological cell. The SEM image of the actual fabricated sensor is shown in Figure 14(a). The concept of measuring heat was based on the resonant frequency tracking of a cantilever in temperature variation due to heat from the biological sample. For the operation of the sensor, the resonating cantilever was placed in a vacuum, and the heat was conducted from the sample through a heat guide. The used configuration is shown in Figure 14(b), which can avoid heat loss from the resonator to the atmosphere and damping in water. Heat releases from the biological cells were detected from the frequency response of the cantilever sensor.



(a)



(b)

Figure 14. (a) Schematic and SEM image of the resonant thermal sensor and (b) Thermal circuit model of the device and device structure [182]

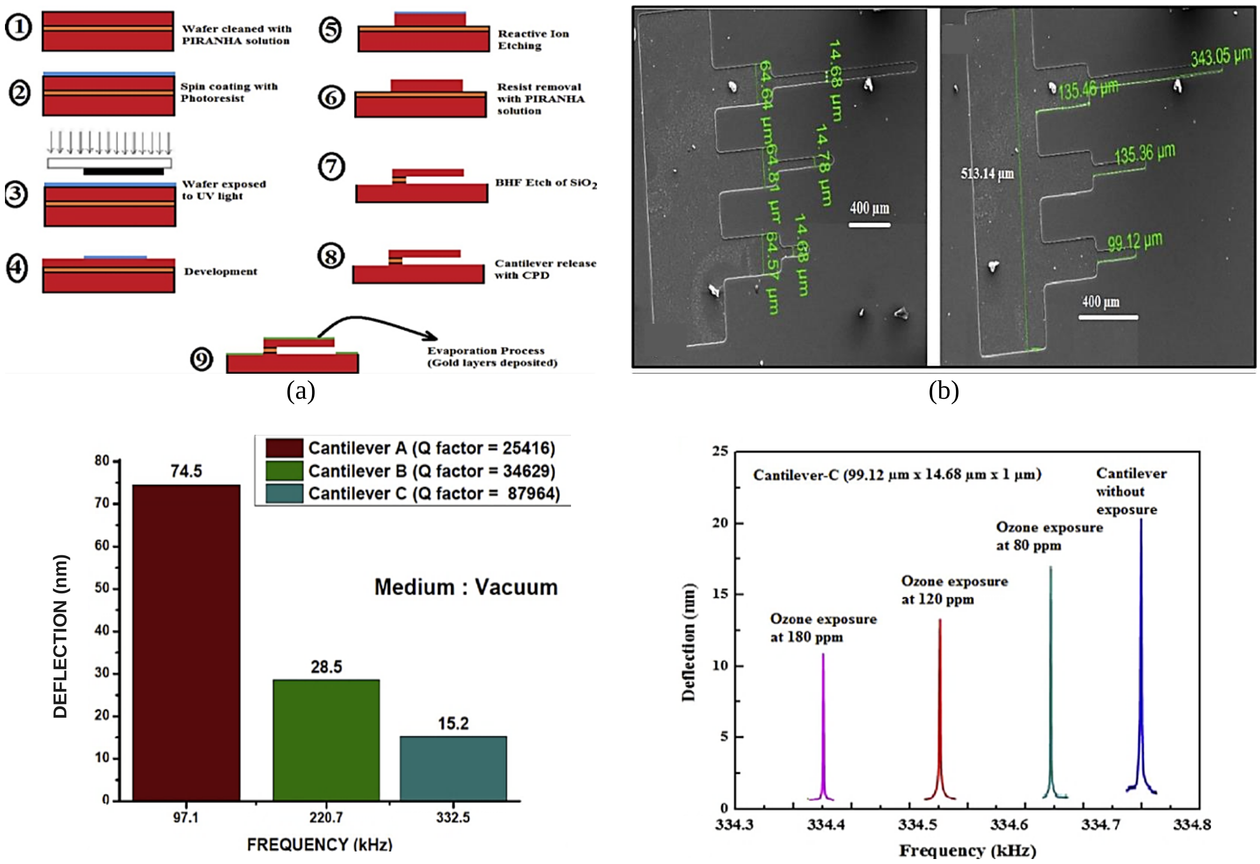
The micro-cantilevers can also be employed for developing infrared sensors. Piezo-resistive-based cantilever sensors have served an important role in the development of infrared detection technology. A piezo-resistive cantilever sensor was developed by Oden et al. [189] for the detection of infrared radiation, containing a heat-absorbing layer coated over it. Gold black works as a good infrared absorber. The cantilever's bending, because of heating causes a change in its electrical resistance, is directly proportional to the amount of heat or infrared absorbed by it. Al, Zn and Pb are some highly temperature-sensitive materials which can be used as coating materials over the cantilever sensors to provide higher sensitivity.

5.3 Gas and Fluidic Sensors

Gas detection is quite important in many applications like measurement of air pollution, gas industries, toxicity detection, explosive gas dripping etc. The micro-cantilevers are also being utilized in the development of gas-sensing devices. Amiri et al. [111] fabricated a micro-cantilever sensor array and used it for ozone gas sensing. MEMS technology was used for the fabrication of the array and LVD was used to get the frequency response of the sensor in an ozone environment. Three cantilevers were presented in the sensor array, out of which the smallest cantilever was found to have the highest sensitivity for ozone detection because of its high structural stability. Figures 15(a) and (b) showed the fabrication process and the SEM image of the fabricated sensor array consisting of three cantilevers of different lengths.

In the same work, it was observed that the smallest cantilever in the array showed the highest Q-factor and resonant frequency with less deflection (see Figure 15(c)). The reason is that the smaller size of the cantilever contributes to its higher stiffness, which results in less energy loss under the damping effect. Figure 15(d) showed the response of the smallest cantilever. In this figure can be observed that the deflection and the resonant frequency of the cantilever decrease as soon as the concentration of the ozone exposer/exposure increases.

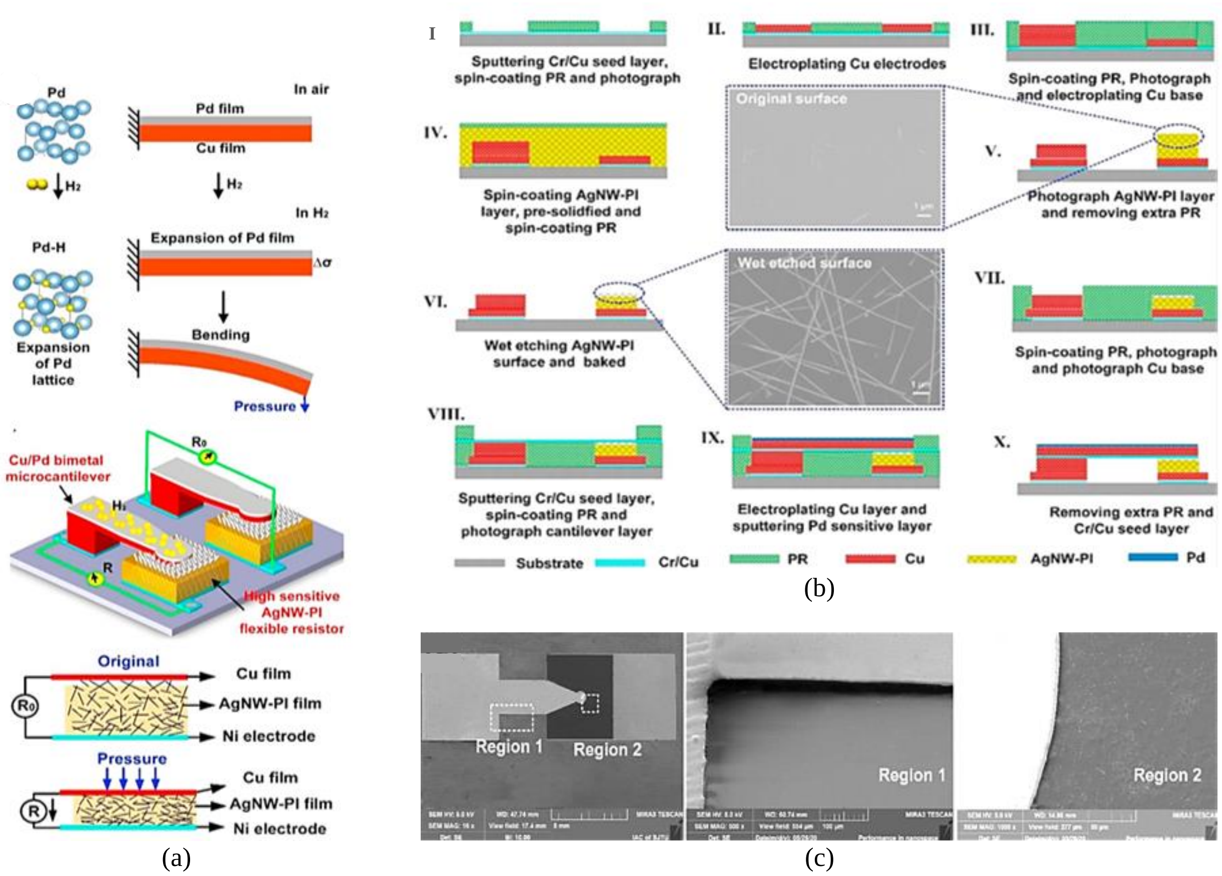
Li et al. [100] proposed a novel design of a cantilever-based hydrogen sensor. The sensor consists of a Pd-coated micro-cantilever and a flexible silver nanowires-polyimide (AgNW-PI) piezoresistor. Figure 16(a) showed the working schematic of the sensor. The hydrogen is absorbed by the FCC structure of the Pd film and randomly occupies the octahedral interstitial sites of the Pd lattice. Thus the top Pd layer of the micro-cantilever is expanded and the bottom Cu layer remains in its original volume, which results in the downward bending of the micro-cantilever. On bending of the cantilever, the effective contact points are formed between the Cu layer and the exposed AgNWs. This changes the resistance between the cantilever beam and the underlying flexible AgNW-PI piezoresistor. The hydrogen concentration can be detected by the change in resistance amount.



(a) (b)

(c) (d)

Figure 15. (a) Fabrication process, (b) SEM images of the fabricated micro-cantilevers array, (c) Resonant frequency and deflection of the cantilevers in vacuum and (d) Responses of smallest micro-cantilever [111]

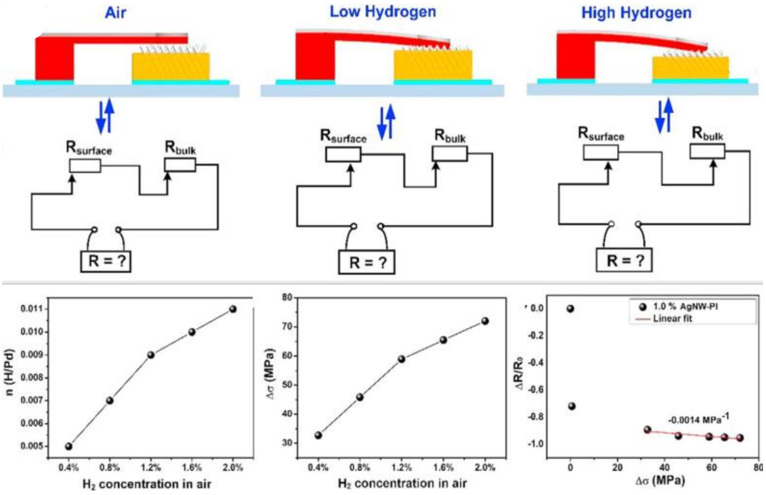


(a) (b) (c)

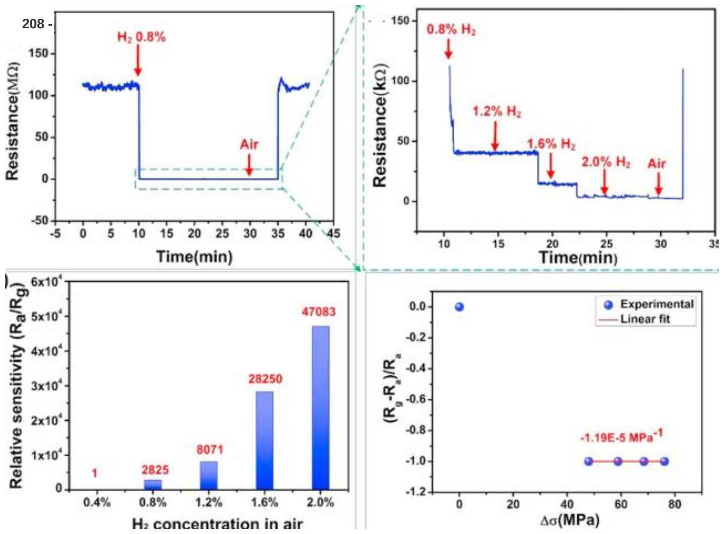
Figure 16. (a) Schematic of the Pd-based bimetal micro-cantilever, highly-sensitive and flexible resistor and hydrogen sensor, (b) Fabrication processes and (c) SEM image of fabricated hydrogen sensors [100]

The fabrication procedure of the hydrogen sensor was based on MEMS techniques, which include sputtering, lithography, electroplating, and chemical mechanical polishing as shown in Figure 16(b). Figure 16(c) showed the SEM images of the fabricated sensor.

Figure 17(a) explains the sensing mechanism of the sensor with different H_2 gas concentrations. The resistance of the circuit is decreased when the sensor is exposed to a higher concentration of H_2. Figure 17(b) revealed that the resistance of the sensor decreases with the increase of the H_2 concentration and the sensitivity of the sensor increases with the increasing H2 concentration. The sensor has ultra-high sensitivity of 2825, 8071, 28250 and 47083 at 0.4%, 0.8%, 1.2%, 1.6% and 2.0% H_2 concentration, respectively. The resistance changes and the stress difference relationship are also shown in Figure 17(b), indicating the sensitivity of the AgNW-PI piezo-resistor is only -1.19×10^{-5} MPa^{-1} [100].



(a)



(b)

Figure 17. (a) The schematic of principle and the relationship of n and H_2 concentration in the air, theoretical pressure at different H_2 concentrations and resistance change at different pressure and (b) Response of the hydrogen sensor under different H_2 concentrations, the relative sensitivity of the hydrogen sensor under different H_2 concentration and changes in resistance under different pressure [100]

Fluidic property measurements like density and viscosity measurement arealso quite important because they play a vital role in various industries like pharmaceutical, automotive, oil exploration and environmental monitoring [180]. The density and viscosities of a fluid can be estimated using different mechanical, electromagnetic and optical sensors [190]. The use of vibrating cantilevers is an embryonic technique for this application. This method is mostly used in online monitoring of fluid flow and density. Microcantilevers comprise different resonant frequencies in different fluids for the reason of their different mass densities. The adjacent fluid of a vibrating cantilever wields an inertial mass load on it by an amount of fluid mass displaced by the cantilever and changes its resonant frequency. The alteration in fluid density results in a resonant frequency shift, but the quality factor remains unaffected by the fluid density. The resonant frequency of a cantilever dipped in a fluid is affected by the fluid density, while the full width at half maximum (FWHM) of the cantilever sensor is influenced by the fluid viscosity as shown in Figure 18 [81, 93].

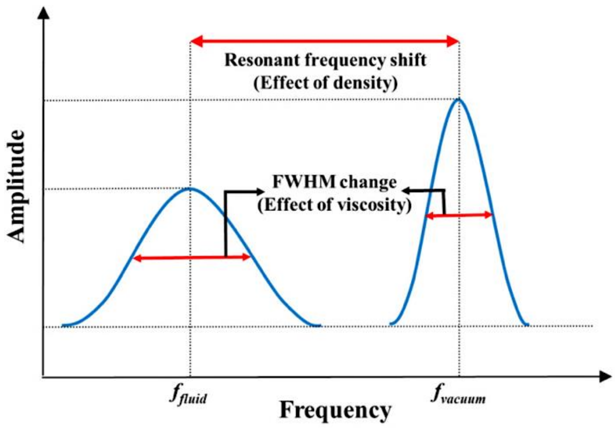
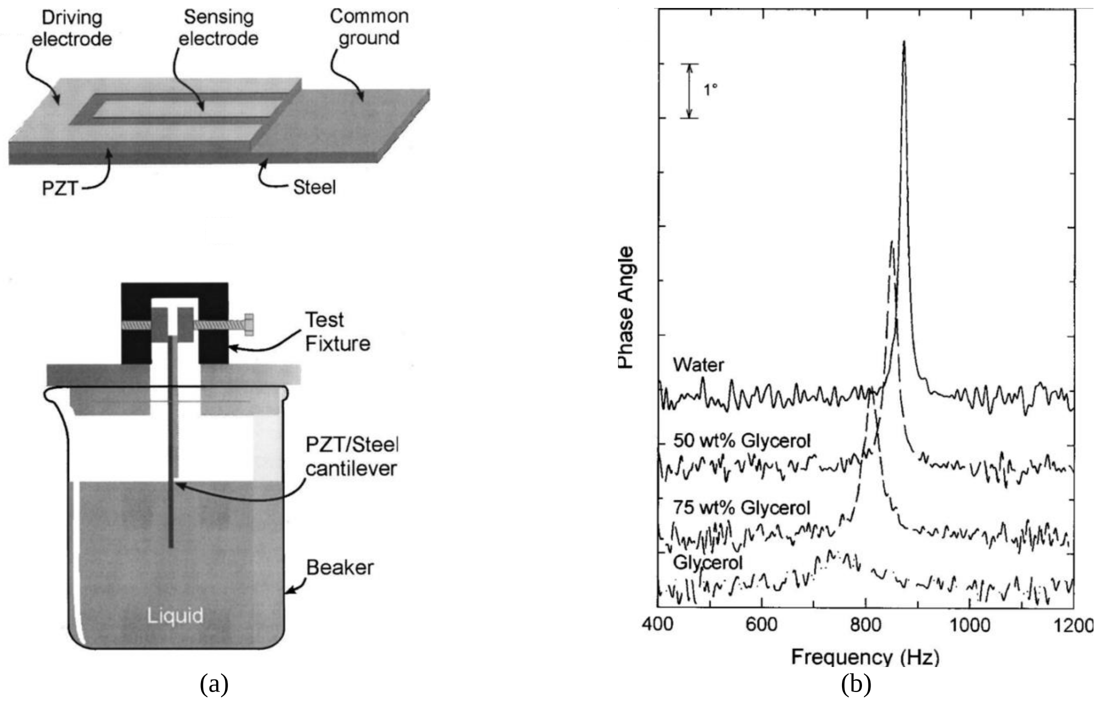


Figure 18. Fluidic load effect on the frequency response of the cantilever

Cantilever sensors with a dynamic mode of operation are also used for the viscosity measurement of the fluids. The fluid viscosity provides a viscous damping effect during the cantilever vibration. The damping results in a decrement in the FWHM and it can be used to measure the fluid viscosity (Figure 18). A cantilever sensor can vibrate through the piezoelectric effect at resonance and be used as the viscosity meter [191]. Compared to the other viscosity measuring methods, the vibrating cantilever sensor technique entails a much lesser volume of testing fluid, which makes cantilever viscosity meters attractive for such applications as MEMS, chemistry, biology and medical science etc [180, 190, 192–194].

Shih et al. [190] examined a piezoelectric unimorph cantilever as a fluid viscosity-and-density sensor. Figure 19(a) showed the cantilever sensor and the fluidic measurement experimental setup. They operated the sensor in the dynamic mode and the frequency response of the sensor in fluidic media was observed for the measurement. The frequency response is shown in Figure 19(b) and it is clear that the resonance frequency of the sensor decreased while the width of its resonance peak increased with increasing glycerol content in the fluidic media. The viscosity and the density of the liquid media were determined simultaneously using these experimentally measured resonance frequencies and peak widths.



(a) (b)

Figure 19. (a) Schematic of PZT/stainless steel cantilever and viscosity sensing experimental set-up and (b) Phase angle vs frequency plot of the PZT/steel cantilever in water and glycerol solutions [190]

5.4 Explosive Detection and Volatile Sensors

The use of traditional techniques for explosive detection is limited because of their longer response time as well as bulky and costly construction. Microcantilever devices are more suitable for such an ultrahigh sensitivity application as the explosives have a very low vapour pressure. Various applications of the microcantilever have been found in the literature for explosive detection [195, 196]. A chemical receptor layer for the explosive vapour molecules on the cantilever surface is required to use the cantilever sensor as an explosive detector. Various researchers are making efforts to fabricate a 'nose-on-a-chip' sensor device for detecting or smelling explosive substances like dogs do. These devices consist of an array of microcantilevers coated with different coating layers that are utilized to sense a particular substance [197, 198]. Microcantilever array sensor used for explosive detection is a great achievement from the point of view of security and preventing large accidents.

Yinon [197] showed the research of the Oak Ridge National Laboratory in which an extremely sensitive explosive detector was developed using a micro-cantilever. In their explosive detection technique, explosive vapour was passed into a chamber containing the sensor and the molecules of explosive vapour were absorbed by the cantilever surface, which was beingheated by a piezoresistive circuit implanted in the cantilever. Because the cantilever was heated, the absorbed explosive molecules go through combustion and produced a large and sudden deflection of the cantilever. This deflection indicates the explosive presence. Zou et al. [199] developed a piezoresistivity-based cantilever sensor for TNT explosive detection. They functionalized it with the dual SAMs (self-assembled monolayers) for TNT detection with a resolubleconcentration level of tens of ppt.Patil et al. [200] also developed the SU-8 nano-composite micro-cantilevers equipped with gold surfaces and reformed with different self-assembled monolayers for the detection of different explosives such as royal demolition explosive (RDX), pentaerythritol tetranitrate (PETN) and trinitrotoluene (TNT). The sensor shows the detection ability at levels below ppt (parts per trillion) within seconds of exposure. The change in resistance ($\Delta R/R$) as afunction of the deflection of the cantilever is shown in Figure 20. This figure also showed the fabricated sensor along with the experimental setup for explosive vapour detection. This sensor platform incorporated with tens of micro-cantilevers functionalized with the different receptors in a single chip can be used for the simultaneous detection of a wide variety of explosive vapours.

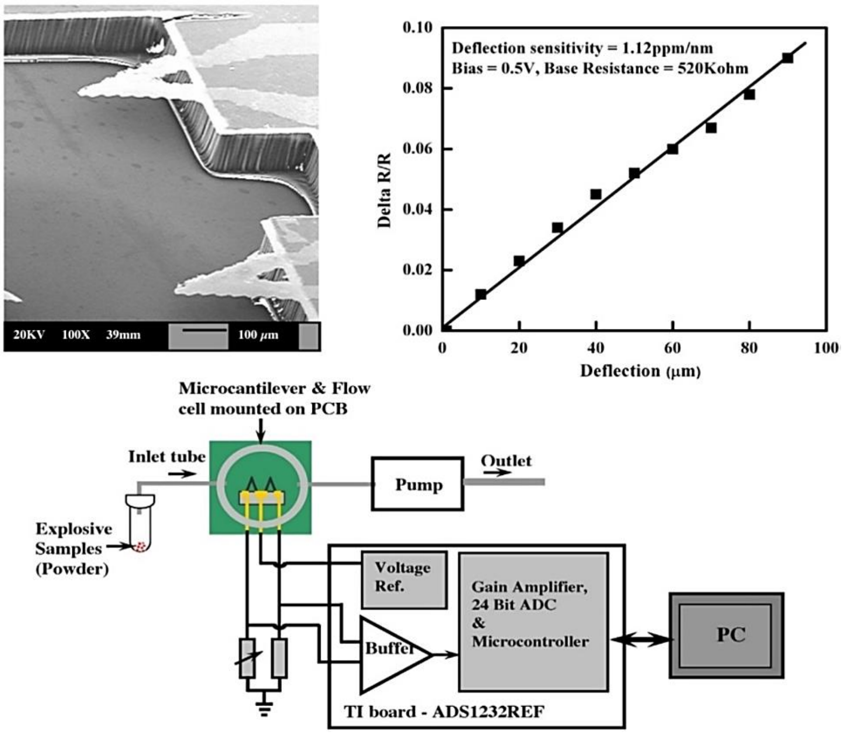


Figure 20. SEM image of the released polymer nano-composite micro-cantilevers, resistance change ($\Delta R/R$) as a function of deflection of the cantilever and experimental setup for explosive vapour detection [200]

Many researchers have been persuaded to support the development of a miniature sensor to detect volatile organic compounds or other volatile materials [201]. Guruprasad et al. [202] presented the analysis of a MEMS cantilever sensor to sense VOCs (acetone and isopropyl alcohol). They used the RF Sputtering technique for the fabrication of the MEMS cantilever sensor with an active coating of PVP and 3-APTES. The PVP-coated sensor is found to have 39% higher sensitivity as compared to the 3-APTES-coated sensor for acetone detection. Further, the 3-APTES coating showed 7.5% higher sensitivity for isopropyl alcohol detection as compared to the PVP coating.

5.5 Under Water Application and Flow Sensor

The micro-cantilevers operated devices such as hydrophones are used in underwater applications. Abdula et al. [109] presented a novel design of a cantilever-based hydrophone. The MEMS microfabrication was done on a silicone substrate and the sensor was fabricated with AlN and Molybdenum (Mo) thin films as the active part and electrode, respectively as shown in Figure 21(a). The SEM images of the fabricated sensor and the cross-configuration are given in Figure 21(b). The LVD was used to analyze the resonance frequency of the fabricated sensors underwater and to judge the sensor's responsivity and directionality. This experimental setup is given in Figure 21(c). An omnidirectional directivity pattern with a maximum sensitivity up to -153 dB was achieved with the fabricated sensors at 5 kHz pulse repeating frequency

(PRF) for the longest cantilever (Figure 21(d)). The higher directionality and wider ultrasonic range can be obtained by combining the cross-configurations with different cantilever lengths and sensitivity to different ultrasound frequency range. The compactness and performance of the presented hydrophone made it most promising for use in underwater acoustics [109]. Flow measurement is also important in many sensing applications. An airflow-sensing device made with eight PVDF cantilever sensors was developed by Hu et al. [112]. The device is capable of amplifying the vibration amplitude of the cantilever, and the cantilever array in the device can simultaneously sense the airflow direction and velocity. Figure 22(a) showed the comparison between the working physics of conventional sensors and newly developed air flow sensors in this research work. The guiding frame of the newly developed sensing device prompts an increase in the pressure difference in the flow on the surface of the PVDF cantilever as compared to the conventional sensor structure.

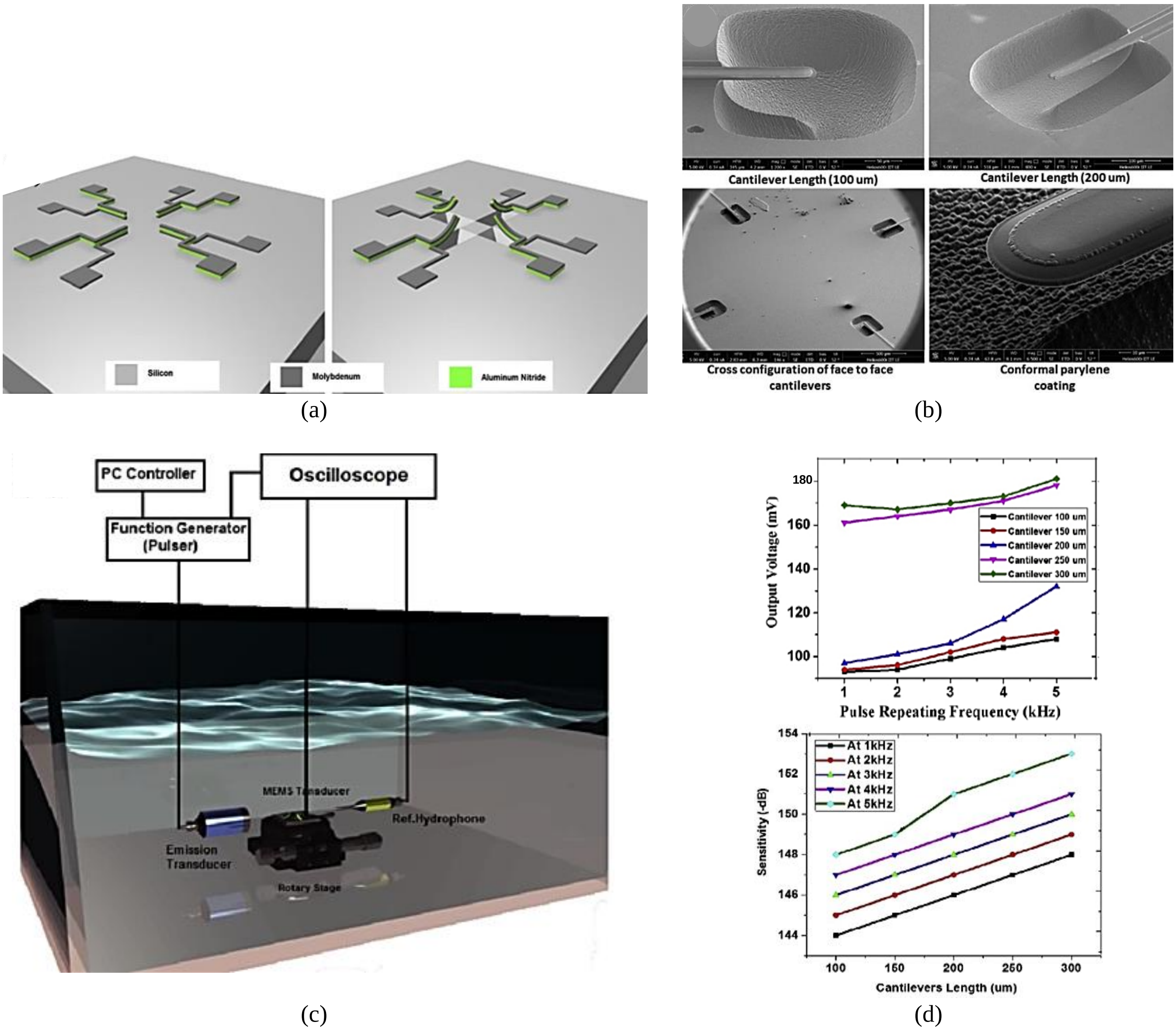


Figure 21. (a) Definition of molybdenum top/bottom electrode and AlN piezoelectric layer (b) SEM images of MEMS fabricated cantilevers, (c) Schematic of hydrophone experimental setup and (d) Output voltages response of the cantilevers and their receiving sensitivity [109]

Figure 22(b) showed the PVDF cantilever sensor made of a two-layer strip, one is a copper sheet and the second is a PVDF film. The connecting electrodes are present at the root of the cantilever. Because of the piezoelectric effect, the PVDF film will produce an electric charge when subjected to strain. This figure also shows the device structure consisting of eight cantilever sensors in it. The experimental set-up of the measurement system using the PVDF sensor array device is given in Figure 22(c). The voltage signal response of the device at an 8.4 m/s flow rate is shown in Figure 22(d). Finally, it was found that by using the new device the vibration amplitudes of the cantilever can be improved to 20 times greater than an exposed cantilever with a conventional airflow sensing array. This study floors the way for further research on the realization of new sensing devices for aircraft [112].

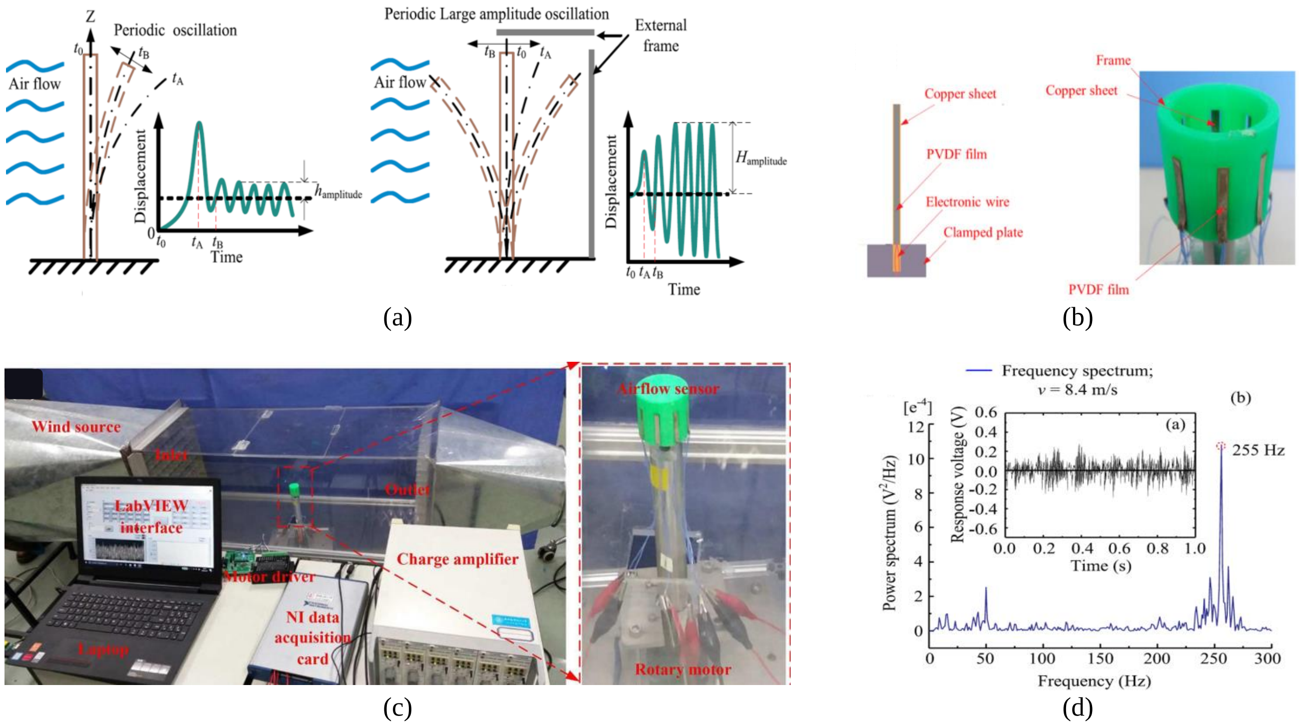


Figure 22. (a) Vibration sensing schematics in the airflow with a conventional cantilever and newly developed PVDF cantilever with the frame, (b) PVDF cantilever and sensor array structure, (c) Experimental set-up and (d) Response voltage signal characteristics of the PVDF cantilever at 8.4 m/s [112]

5.6 Magnetic and Electrical Sensor

The research of Indianto et al. [59] explored the magnetic sensing phenomenon of a magnetostriction-based magnetic cantilever sensor made of FeGa and PZT. The material deposition and etching processes were used to fabricate the FeGa/PZT cantilever sensor. The design of the fabricated sensor is shown in Figure 23. This FeGa/PZT cantilever sensor reflects a sensitivity of 5.47 Hz/mT in a static DC magnetic field in the perpendicular direction. The detection limit of the sensor was found to be 3.66 µT, which can be further improved by reducing thermal noise using a narrow, thin, and long cantilever design with a high Q-factor. In the vicinity of a magnetic field, the magnetic domain of the cantilever's magnetostrictive material reorients in a specific direction and deforms the cantilever. The fabrication process of the sensor and the final fabricated device are shown in Figures 23(a) and (b). The sensing and analysis were done for the parallel and perpendicular magnetic field directions. Additionally, both positive and negative field effects were observed in Figure 23(c).

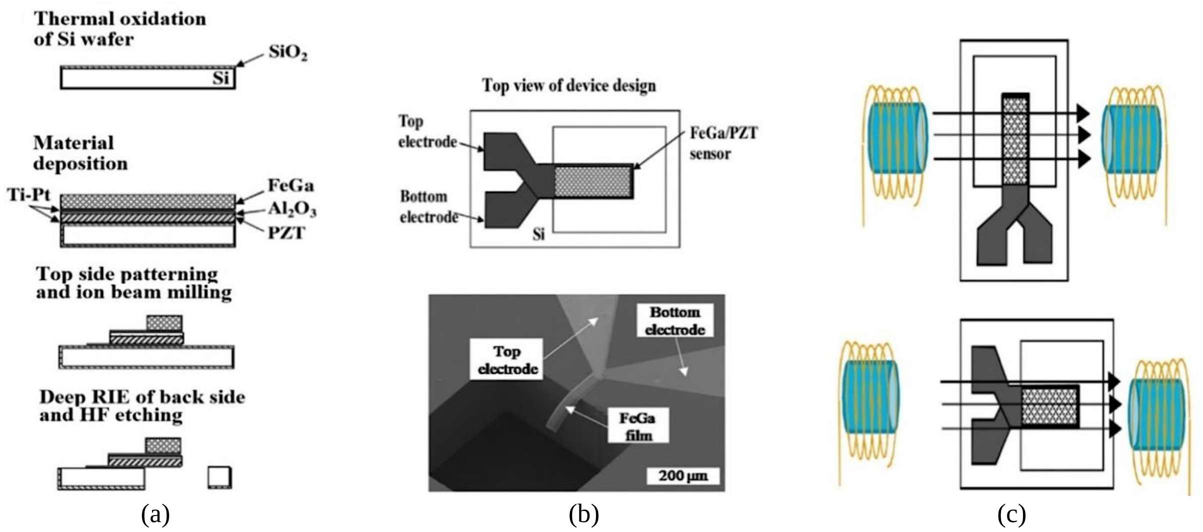


Figure 23. (a) Fabrication process (b) Top view of the device and fabricated FeGa/PZT cantilever magnetic sensor and (c) Static DC magnetic field setup [59]

The high sensitivity, large dynamic range and ease of fabrication of microwave power sensors make them promising in the field of satellite and radar systems [203, 204]. Many researchers have explored capacitive, thermistor and thermoelectric-based microwave power sensors [205, 206]. Capacitive MEMS power sensors, utilizing cantilever beam structures, have been shown to effectively measure intermodulation distortion, demonstrating their potential for precision applications in high-frequency domains [205]. Further advancements have analyzed the high-power handling capabilities of these capacitive sensors, particularly at X-band frequencies, highlighting their robustness under demanding conditions [206]. Enhancements in dynamic range through innovative designs of MEMS cantilever beams have also been reported, making these sensors more versatile for microwave power measurements [207]. Additionally, thermistor-based flow sensors, such as those employing self-heated a-Ge thermistors in a Wheatstone bridge configuration, provide accurate sensing solutions, bridging the gap between microwave power sensing and thermal measurement techniques [208]. These studies collectively emphasize the diverse approaches to optimizing microwave power sensor technologies. In the research work of Li et al. [209], the capacitive microwave power sensor was fabricated using the GaAs MMIC process and the electro-mechanical behaviour of this microwave power sensor was investigated (Figure 24(a-c)). Figure 24(d) showed that the output response of this sensor exhibits non-linear characteristics under high power levels (more than 1000 mW). The results showed three regions linear region (1-1000 mW), saturated region (1000-2500 mW), and over-saturated region (2500–4000 mW). Their corresponding sensitivities are 2.8 fF/W, 1.03 fF/W, and 0.32 fF/W at 10 GHz, respectively.

The electric field measurement is effective in replacing the traditional voltage transformer to realize the noncontact voltage measurement. This reduces maintenance and operational costs. Figure 25(a) showed the working principle of the E-sensor, in which a silicone cantilever sensor bent up because of the electrostatic field force (due to an external electric field) acting on the metal film bonded over it. A piezoresistive E-sensor was fabricated using MEMS technology by Han et al. [210]. The structure of that E-sensor is shown in Figure 25(b). This sensor consists of four cantilever structures, which were displaced under the electrostatic force, and the generated strain was converted into the signals by the piezoresistive characteristic. The piezoresistors in the fabricated sensor are connected to form a WBC, as shown in Figure 25(c).The authors showed that their sensor has the advantage of low cost, mass production and small size with low power consumption. The four E-sensor were fabricated with different dimensional parameters as S1 (1250 μm ×10 μm), S2 (1750 μm ×10 μm), S3 (2250 μm ×10 μm), and S4 (1750 μm ×5 μm). The left side of Figure 25(d) showed that the increase in cut-off frequency can be achieved with a decrease in sensor response. Therefore, the dimensional parameters of the sensor should be designed according to the application required. Figure 25(d) showing the frequency response of the sensor in different electric fields, makes it clear that changing electric field strength does not affect the cut-off frequency of the sensor. The signal-to-noise ratio of the sensor output signal is high at higher field strengths.

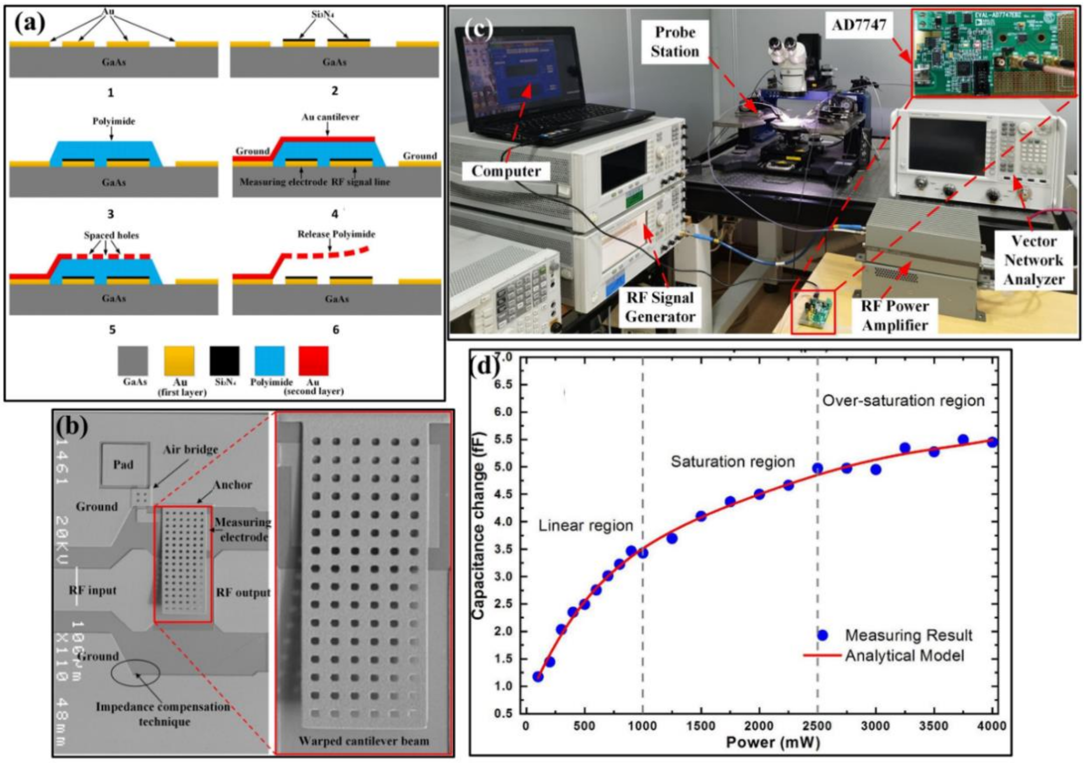


Figure 24. (a) Fabrication of the CMPS, (b) SEM image of the CMPS, (c) Experiment set-up of the DUT and (d) Capacitance change versus microwave power at 10 GHz [209]

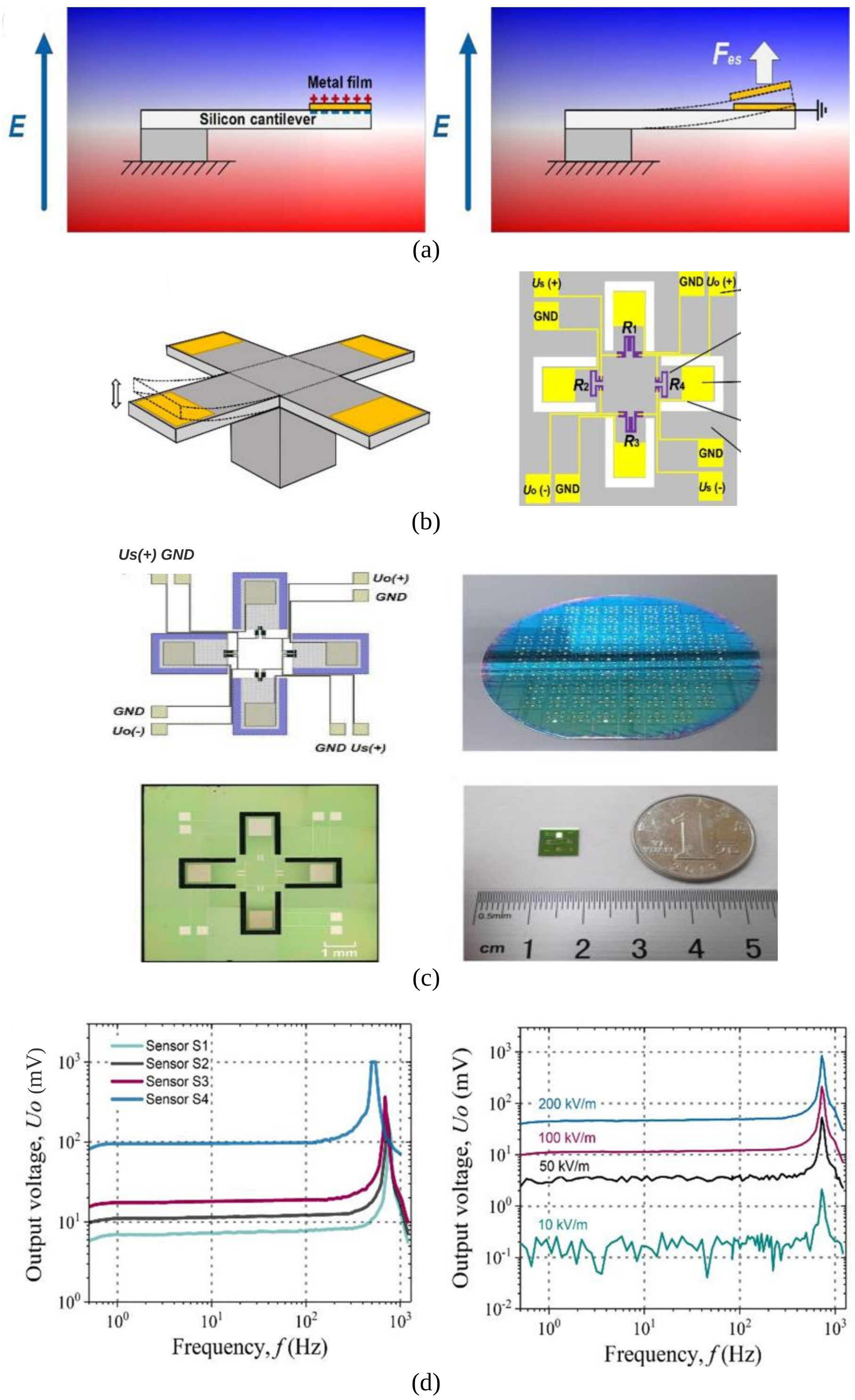


Figure 25. (a) Response of a silicon cantilever with metal film in the electric field, (b) Structure of the E-sensor, (c) Fabricated micro-E-sensor and (d) Frequency response of E-sensors with different dimensional parameters (left) and frequency response of sensor S2 (right) [210]

5.7 Bio-Sensing

The development of sensors based on the bending of microcantilevers leads towards the fabrication of biochips [211–213]. These biochips have potential advantages over conventional detection methods [214, 215]. The biochips in the mechanical detection system measure and detect the deflection of the cantilever, which further leads to the sense of physical entities [214]. Biochips can also be used for the screening and detection of some critical diseases like cancer [216]. Microcantilever sensors have a wide range of applications in the fields of clinical biochemistry and medical diagnosis as well [217]. They can be utilized for the diagnosis of coronary heart disease. Arun et al [98] utilized the micro cantilever-based sensor for cancer diagnosis. Lee et al. [218] also detect the prostate-specific antigen (PSA) through the resonant frequency shift of the piezoelectric microcantilever.Hansen et al. [219] used the microcantilever for the discrimination of DNA single ¬nucleotide mismatches. Arntz et al. [220] used the deflection of the microcantilever to detect myoglobin, which was bound to the anti-myoglobin coated on the surface of the cantilever. A nanomechanical cantilever array was utilized by McKendry et al. [221] for multiple label¬-free bio-detection. Raiteri et al. [222] determined the herbicide concentration in the liquid environment through a microcantilever sensor. The pesticide DDT detection is also done by Alvarez et al. [223] by using microcantilevers.

Oyunbaatar et al. [99] showed that the surface topography of the device is quite important in tissue engineering applications. Their research work presented a modified surface of a cantilever-based device with stress-directed micro-wrinkles. The fabricated device was a PDMS cantilever with a thin Au-μwrinkle film over the surface as shown in Figure 26(a) and (b). During MEMS fabrication the wrinkles were formed naturally when the compressive stress applied to the cantilever surface exceeded the critical compressive stress of the material (Figure 26(b)). These wrinkles on the surface provide improved alignment of cardiomyocytes on the surface of the cantilever, which further assists sarcomere alignment. The electrical conductivity of cells in the tissue culture was enhanced by the Au layer on the cantilever. The metallic wrinkle pattern over the PDMS cantilever increases the expression levels of proteins related to intracellular adhesion and contraction significantly. The proposed design of the cantilever is versatile and may be used to screen for drug-induced cardiotoxicity during drug development. The wrinkled cantilever showed a high degree of bending displacement on days 10 and 11 of cell culture as shown in Figure 26(c). The contraction forces in the absence and presence of the Au- μwrinkled cantilever were approximately 1.2 μN and 2.34 μN, respectively. On the other hand, the displacements of the Au-μwrinkled and flat PDMS cantilevers reached approximately 600 μm and 300 μm, respectively.

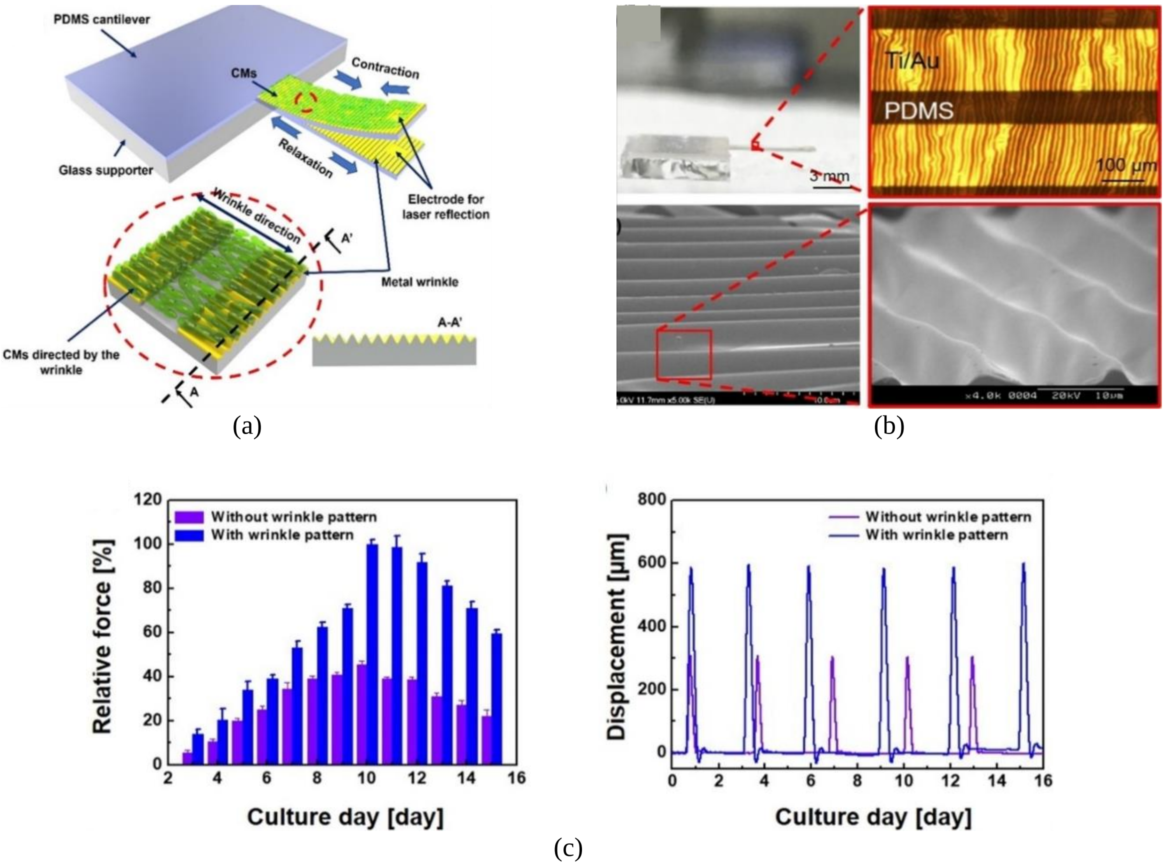


Figure 26. (a) Polymer cantilever with a micro-wrinkled conductive substrate, (b) Optical and SEM images of the fabricated cantilever with Au-μwrinkles and (c) Contractile characteristics of the flat and Au-μwrinkled PDMS cantilever: day-wise relative contraction force (left) and bending displacement (right) [99]

A modified design of a micro-cantilever sensor for the detection of early stages of cancer was developed by Upadhyaya et al. [223]. The effect of geometrical modification on the design is investigated in this work. The presented sensor utilizes an integrated optical microring resonator in it for the detection phenomenon. A channel is made at the free end of the cantilever for loading the sample as shown in Figure 27(a). The channel is coated with the antibody which interacts with the CAE antigen and the interaction of these antibodies with the antigen increases the mass of tumour biomarkers on the coated surface of the micro-cantilever. This increment of mass was used for detection. The optical microring resonator is shown in Figure 27(b). It consists of a hexagonal lattice of 21 × 33 μm size with arrays of silicon micropillars. The silicone micropillars are removed for creating the six hexagonal rings, and input and output waveguide. The input and output bus waveguides are coupled with the hexagonal rings. The light source was kept at the input port for excitation and a detector at the output port for monitoring the change in resonant wavelength on the application of pressure at the free end of the cantilever. Figures 27(c) and (d) showed the transmission spectrum obtained for the rectangular and triangular profiles of the micro-cantilevers. As soon as the CEA molecules increase on the cantilever, the pressure, and the peak wavelength shift increase. For the rectangular cantilever sensor, the transmission efficiency was 93% at a pressure of 0.5 MPa. This efficiency was found to be 80–86% for 1-2 MPa pressure.

The quality factors were 3805 and 3117 at 1.5 MPa and 1 MPa pressure, respectively. The maximum pressure sensitivity for rectangular microcantilevers is around 0.01 nm/MPa. The triangular shape of the microcantilever results in less inflexibility and a large deflection for the same range of pressure. In the case of the triangular cantilever, the highquality factor 11,458 was found for the pressure of 0.5 MPa and the lowest Q-factor 7002 was found at the pressure of 1.5 MPa. Figure 27(d) clearly showedthat there is a steady increase in transmission efficiency after a pressure of 1 MPa. Therefore, it can be concluded that the proposed triangular structure has the best accuracy compared to the other structures. The sensitivity and quality factors of the modified design are quite high. Thus, the proposed sensor has remarkable applications in the detection of CAE antigen, which is an early indicator of colon cancer present in the human body.

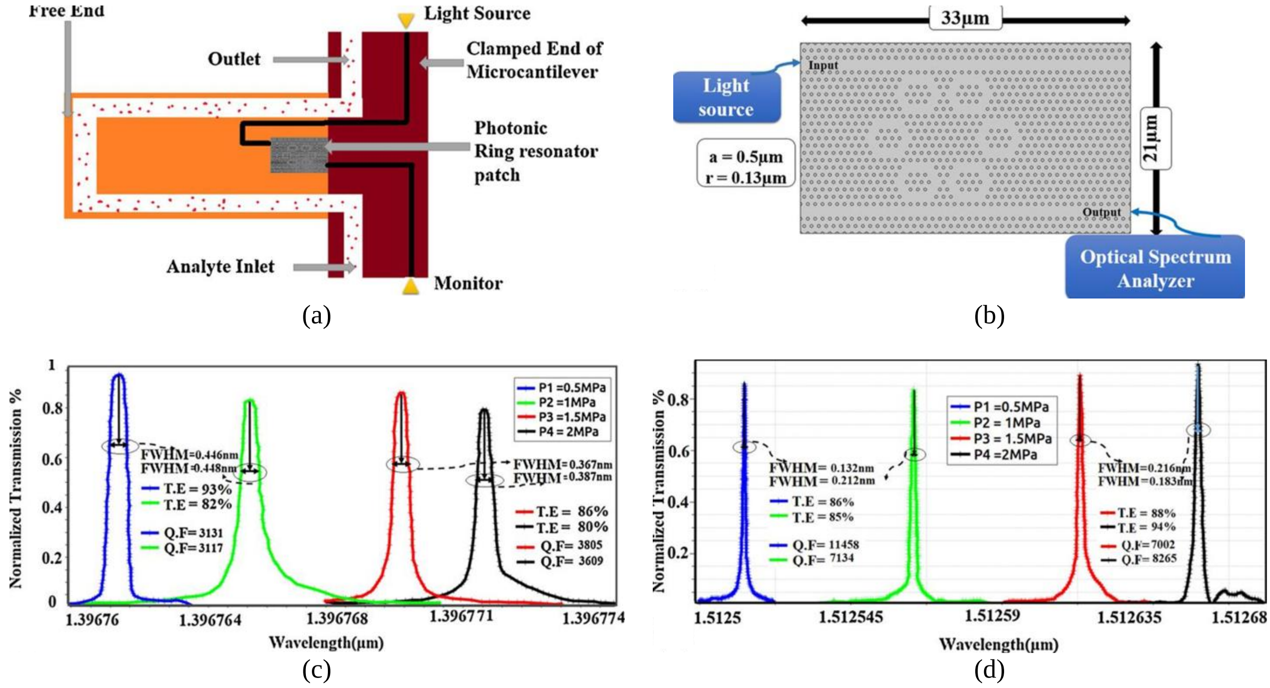


Figure 27. (a) Micro-cantilever sensor with an integrated photonic ring resonator, (b) Photonic ring resonator structure, (c) Transmission spectrum of rectangular micro-cantilever and (d) Transmission spectrum of triangular micro-cantilever [223]

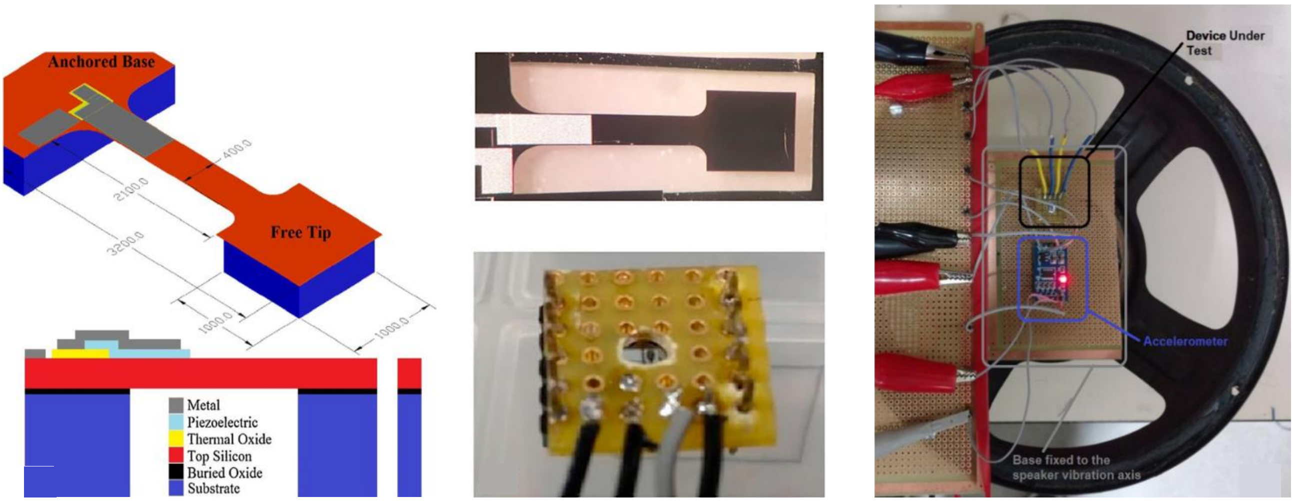
In recent years, micro-cantilever-based bio-sensing has grown to include a wide range of methods and instruments to measure the biological targets and processes that are important in medical applications such as diagnostics, environmental monitoring [202], bio-warfare, and elementary research [224–226].

5.8 Vibration Sensor Cum Energy Harvesters

The vibrational energy harvesters need to be developed for powering the miniature device in sensing applications [227]. Out of many energy harvesting techniques, photovoltaic transduction provided the highest energy density. But because of the requirement for a continuous source of light, the method is quite unreliable. In energy harvesting applications, vibrational transduction using piezoelectric, electrostatic, and electromagnetic mechanisms has also proven to be very useful. Piezoelectric harvesters play an important role in energy harvesting devices due to their simple design, ease of integration, and high output energy density [228, 229]. Oliveira et al. [230] presented a vibrational sensor cum energy harvester cantilever device, which was capable to harvest a good amount of energy from the common ambient source of vibration because of the very low resonance frequency of the cantilever device.

In this MEMS-based micro-cantilever, the AlN piezoelectric film is used to harvest and sense vibrational energy. The device was fabricated with a very low resonance frequency of 163 Hz to meet the requirement of high energy harmonics present in common ambient vibrations. A cost-effective experimental setup shown in Figure 28(c) was also developed for the characterization and a power output of 0.491 µW at the resonance frequency of 163 Hz for a vibration intensity of 10 ms^{-2} was obtained with this device. A 3-D model of the device with cross-section and the fabricated device is shown in Figure 28. The figure also showed the fabricated device and the experimental setup used for the characterization and energy harvesting.

Rashmi et al. [231] fabricated a piezoelectric-based P(VDF-TrFE) microcantilever sensor using MEMS technology and they used it for small vibration sensing and energy harvesting. Figures 29(a) and (b) showed the cantilever and beam-based sensor design which were fabricated using the MEMS technique. The effect of the cantilever's geometrical parameters on the resonant frequency, voltage and power output is studied. The measurements were carried out using an LDV. The measurement results revealed that decreasing the length and width of the sensors increased their resonant frequency, with the longest and widest sensors exhibiting the maximum deflection (see Figure 29(c)). The beam design of the sensor showed a lower voltage output (because of lower displacement) and higher resonant frequencies as compared to the cantilever design of the sensor of similar dimensions (see Figure 29(d)). Thus, the reliability and the life cycle of the beam design of the sensor are longer, and they can be preferred as practical devices.



(a) (b) (c)

Figure 28. (a) Proposed structure design (μm) and transversal section image, (b) Fabricated device and DUT and (c) Experimental set-up: adapted vibrational device with the test sample connected with the accelerometer [230]

Rashmi et al. [231] fabricated a piezoelectric-based P(VDF-TrFE) microcantilever sensor using MEMS technology and they used it for small vibration sensing and energy harvesting. Figures 29(a) and (b) showed the cantilever and beam-based sensor design which were fabricated using the MEMS technique. The effect of the cantilever's geometrical parameters on the resonant frequency, voltage and power output is studied. The measurements were carried out using an LDV. The measurement results revealed that decreasing the length and width of the sensors increased their resonant frequency, with the longest and widest sensors exhibiting the maximum deflection (Figure 29(c)). The beam design of the sensor showed a lower voltage output (because of lower displacement) and higher resonant frequencies as compared to the cantilever design of the sensor of similar dimensions (Figure 29(d)). Thus, the reliability and the life cycle of the beam design of the sensor are longer, and they can be preferred as practical devices.

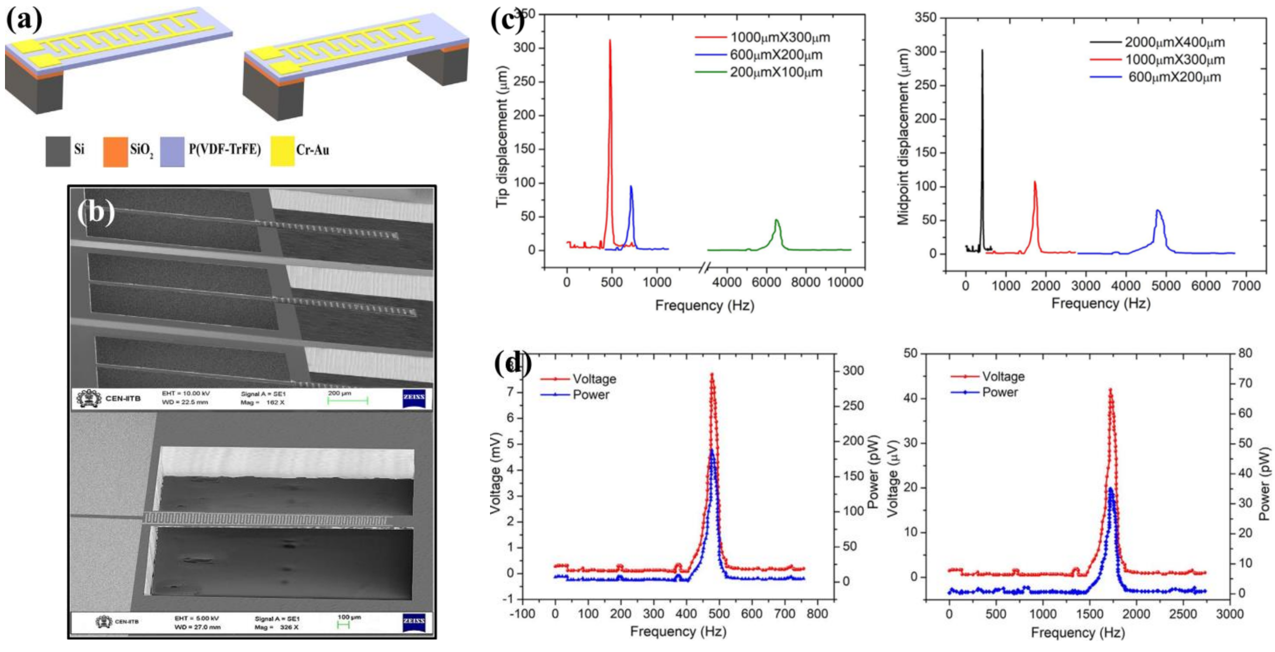


Figure 29. (a) Schematic of P(VDF-TrFE) micro-cantilever and micro-cantilever beam, (b) FESEM images, (c) Tip displacements and midpoint displacements v/s frequency for micro-cantilevers (left) and micro-cantilever beams (right), respectively and (d) Voltage and power output v/s frequency for micro-cantilevers (left) and micro-cantilever beams (right) [231]

6. CURRENT CHALLENGES, PROPOSED SOLUTIONS, FUTURE DIRECTIONS, AND CONCLUSION

Micro-cantilever sensors have gained considerable attention due to their numerous advantages, including higher aspect ratios, lower fabrication costs, multiple operational modes, label-free detection, array compatibility, and easy integration with on-chip electronic circuits. These sensors exhibit superior sensitivity compared to conventional sensing devices, making them versatile for applications such as sensors, transducers, resonators, relays, and switches across various mediums like air, liquid, and vacuum. Despite their potential, several challenges persist that must be addressed to unlock their full capabilities. Limited work has been conducted on optimizing the design and material properties of MEMS-based cantilever sensors to enhance their robustness, accuracy, and reliability under diverse environmental conditions. Achieving large-scale production while maintaining consistent quality and performance remains a challenge. Additionally, these sensors are susceptible to external noise, environmental interference, and thermal fluctuations, which can compromise their sensitivity and stability. Customizing micro-cantilever sensors for specific applications, such as chemical, physical, or biological sensing, adds complexity to their development, and despite their lower production costs, the initial investment in research, manufacturing infrastructure, and system integration can be a barrier to widespread adoption.

To overcome these challenges, several solutions have been proposed. Innovations in materials, such as the use of nano-composites, graphene, and other two-dimensional materials, can significantly improve sensitivity, durability, and operational range. Advanced fabrication techniques, including atomic layer deposition and 3D printing, hold promise for enhancing scalability and reducing variability. The development of algorithms and integrated systems for noise reduction and thermal compensation can improve sensor reliability under varying conditions. Integrating micro-cantilever sensors with emerging technologies, such as artificial intelligence and machine learning, can expand their utility in real-time data analysis and predictive modeling for applications like healthcare diagnostics and environmental monitoring. Collaborative research between academia and industry can accelerate the development of tailored solutions for specific challenges.

The future of micro-cantilever sensors is highly promising, with potential applications and market growth in various domains. Advancements in miniaturization are expected to lead to the development of nano-scale cantilever devices, enhancing sensitivity and reducing power consumption. Dynamic analysis, including higher-order vibration modes and interactions with intermolecular forces, represents an exciting area for further research. A great amount of literature has already investigated the diverse applications of micro-cantilever sensors, and the advancement in miniaturization continues to drive demand for smaller molecular diagnostic devices. This reflects the growing importance of micro-cantilever-based sensors in the market. The global market of micro-cantilever sensors can be divided based on their mode of operation, application, operational medium, and region. In recent years, the gaseous sensing segment of micro-cantilevers has held the major portion of the market and is expected to maintain its dominance. The healthcare segment of the global market is also expected to grow significantly in the coming years. MEMS cantilever sensors are actively shaping the future of chemical, physical, and biological sensors. Geographically, North America holds the largest share of the cantilever-based market, with Asia-Pacific following as the second-largest region, and Europe in third place.

Despite these advancements, micro-cantilever devices remain underexplored, particularly in the optimization of MEMS-based cantilever sensors, which still have a wide scope for future research. The dynamic analysis of micro-cantilever devices, where cantilevers interact with the sample surface via intermolecular forces, holds a bright future. Furthermore, research into the higher-order modes of vibration of these cantilevers presents an intriguing field of study. Recent advancements in micro-cantilever devices are guiding researchers toward the development of nano-cantilever devices, which promise even greater sensitivity and efficiency. By addressing current challenges, leveraging material innovations, and exploring uncharted territories, micro-cantilever sensors are poised to revolutionize diagnostics, sensing, and actuation technologies, driving innovation in both research and industry.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest to report regarding the present study.

AUTHORS CONTRIBUTION

S. Chauhan (Roadmap preparation; Writing-original draft; Formal analysis; Investigation; Review & Editing; Revison)

S. K. Mishra (Writing; Formal analysis)

A. Sharma (Review & Editing)

M. Z. Ansari (Project administration; Supervision; Resources)

AVAILABILITY OF DATA AND MATERIALS

The data supporting this study's findings are available on request from the corresponding author.

ETHICS STATEMENT

This review adheres to ethical research standards, with proper citations and no involvement of human or animal subjects.

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