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Survey on design of MEMS gas sensors integrated with microheaters

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Abstract: In this paper, the predominant emphasis has been made on exploring different existing literatures or researches pertaining to gas-flow sensor design and its implementation with Micro-Electro-Mechanical System (MEMS). Though, the design of a gas senor and MEMS technology often depends on the selection of material and structural constructs, in this survey different literatures and allied materials, efficiency and limitations of the different materials, MEMS design etc., are discussed. Additionally, suitability of the MEMS interfaced gas sensors over different temperature or operating conditions are also discussed in this review letter. This study revealed that selection of the material based on its temperature (behavioral) dependency can be efficient to enable optimal gas sensing. Solutions like Micro-heater MEMS can be the suitable solution; though selection of materials for the different layers such as heaters, substrate etc. remains a challenge. The material with low thermal expansion coefficient and better thermal distribution can be an optimal solution to achieve higher sensitivity. Additionally, to cope up with drifts which often take place at high temperature, metal electrodes made up of Fe, Ni, Co, T, and Platinum can be considered. The augmentation in Micro-heater geometry can also help achieving uniform thermal distribution over high temperature and hence can enable sensitive and reliable performance. To examine flow rate, displacement of a micro-fabricated paddle or fluidic gyroscope sensor can be considered. As MEMS fabrication semi-conductor material can be considered, which despite of high thermal expansion can enable cost-efficient solution. On the other hand, the use of metal electrodes as stated above can reduce thermal expansion and hence can achieve an optimal solution.
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Keywords- Gas Sensor, Gas Flow Rate analyzer, Micro-Electro-Mechanical Sensor, Complex Gas sensing Environment.

INTRODUCTION

The upsurge in the establishment of industries has undeniably led to the economic growth of the different nations but has however also led to a rapid escalation in emission of toxic gases and other hazardous environmental pollutants. Hence, accurate monitoring of toxic gases and detection of environmental pollutants has become an inevitable concern during the recent years. In order to reduce pollution caused by expansion of manufacturing industries operating from advance countries to developing countries, strict regulations have to be imposed. In this regard, designing of robust, low cost and portable sensors is an essential requirement in order to develop new range of chemical sensors with enhanced sensitivity. This has been serving as a motivation for the academia industries to revitalize the classical sensors and consequently a continuing effort to miniaturize sensors and optimize the heater dimensions has been made. The industries are encouraged to exhibit a significant size reduction (up to micrometer dimensions) of sensors as it would optimize the sensitivity and selectivity towards the toxic gases. This advancement has resulted primarily from the extensive design and fabrication infrastructure within the semiconductor industry for the manufacture of silicon integrated circuits. Silicon micromachining has led to the development of many types of miniature sensors and actuators, commonly known as Micro Electro Mechanical Systems (MEMS) [1]. As the name implies, MEMS devices involve a mechanical response as part of the signal transduction or actuation process. The primary advantages of MEMS devices are miniaturization, multiplicity, and microelectronics compatibility. We are surrounded by various toxic and harmful gasses, which can even lead to death. Quick detection of such gasses is the need of the hour. Various researches have been conducted to make gas sensors highly selective and sensitive. Gas sensors based on various technologies are available in the market. MEMS based gas sensors are widely used to detect

Different types of gasses. MEMS are the combination of both electrical as well as mechanical components. It is the amalgamation of both electrical and mechanical components. There currently exist several different types of MEMS chemical sensors. Each operates with a different method, e.g., capacitive, thermal, resistive, etc., and used for specific tasks. They are fabricated using Integrated Circuit (IC) batch processing techniques and can range in size from a few micrometres to millimetres. These devices (or systems) have the ability to sense, control and actuate on the micro scale, and generate effects on the macro scale. MEMS can be found in systems ranging across automotive, medical, electronic, communication and defence applications. The current MEMS devices include accelerometers for airbag sensors, inkjet printer heads, computer disk drive read/write heads, projection display chips, optical switches, micro-valves, biosensors and many other products which are manufactured and shipped in high commercial volumes. At microscopic level, various sensors like thermal sensors, gas sensors, pressure sensors, and chemical sensors can be designed [2][3].

Noticeably, there are various MEMS based chemical sensors are widely used in gas detection and each operates with different criteria like capacitive, thermal, resistive, etc.,. These sensors are fabricated using integrated circuit (IC) batch processing techniques and can range in size from a few micrometres to millimetres. These sensors have the ability to sense, control and actuate on the micro scale, and produce the effects on the macro scale. Gas detection sensors are developed to ensure the level of various harmful gases within in an acceptable range. A chemical sensor consists of a transducer and an active layer to convert the chemical information into electrical signal like frequency change, current change or voltage change. There are different gas sensor technologies are used to detect the toxic gases namely, catalytic sensors, thermal conductivity gas sensor, electrochemical gas sensors, optical gas sensors, infrared gas sensor, semiconductor metal oxide sensor and acoustic wave gas sensors [4]. Among these technology semiconductor sensors are play vital role towards detection of concentration of target gases. The basic Structure of Semiconductor Metal Oxide (SMO) Sensor is illustrated in the Fig. 1. Structurally, a gas sensor comprises the following key layers.

- *Substrate,*
- *Insulating platform,*
- *Micro-heater,*
- *Integrated electrodes, and*
- *Sensing layer.*

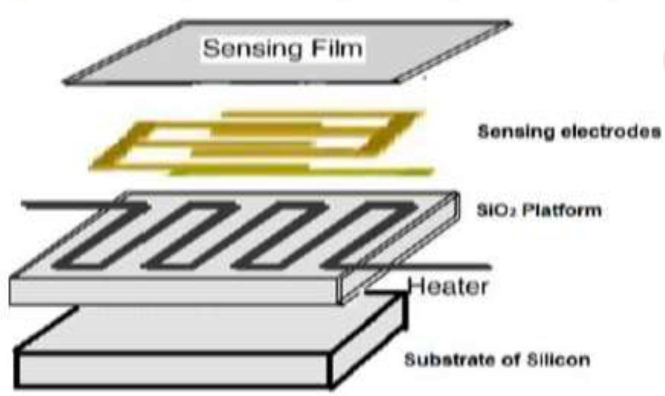

Fig. 1: SMO based gas sensor structure

Substrate is used as bottom layer which provide base to the heater. The most popular substrate is silicon because it has uniform mechanical properties. Insulating platform is the layer present between the substrate and micro-heater. To avoid direct damage to the substrate as well as to reduce the heat loss insulating platform is used. In order to detect the target gas effectively, micro heaters are used in the metal oxide gas sensors. Heating of the micro heater is carried on basis of joule of heating. The micro heaters are applied in humidity sensors, pressure sensors and gas sensors. Integrated electrodes are placed under the sensing layer and used to identify the variations which occur in resistance of the metal oxide sensing surface when it responds to gases. Integrated is nothing but the digit like pattern of electrodes which used in resistance measurement when the gas is absorbed on the layer. Conductivity of the material is changed when the sensor is reached with the atmospheric chemicals. Integrated chemical sensors are very popular because it is cost efficient. Metal oxide sensing layers can use many materials depending upon the gas to be sensed and have good sensitivity towards hazardous gases. The conductivity of this layer varies according to the gas concentration present around [5].

SMO sensors provide a robust and low-cost solution and that can be evaluated with simple electronic systems. SMO like SnO2, ZnO, and TiO2 were used for detecting poisonous (CO) and inflammable gases (such as Methane CH4) by their change in conductivity. However, Conventional SMO sensors require hundreds mill watts of power consumption per sensor since it operates at 300 ◦ C or higher. Embedding conventional SMO sensors in battery-operated devices leads to unacceptable drain on stored energy and it limits the battery life time. To achieve low power consumption the sensor, require elevated operational temperature this can be obtained from pellistors which is applied in the applications such as worker safety, process monitoring, environmental regulation and personal health monitors [6]. The overall reduction in power consumption is achieved by reducing the size of the SMO sensor, and this can be obtained by applying micro-hotplates or micro-heaters because it uses less space and power than the conventional SMO heaters, but have shorter thermal response time [7-22]. In metal oxide sensors, oxidation or reduction process that takes place on the sensing layer occurs at a specific temperature. Oxidation or reduction decides the number of free electrons on the layer which either increases or decreases the conductivity of the layer. Micro heater plays a significant role in achieving the adequate temperature for the reaction. The parameters like uniform heating, low power consumption and mechanical stability are necessary to consider in the design of micro heater.

Semiconductor gas sensor uses the surface adsorption properties of semiconductor to identify the concentration of the various gases which occur due to the change in resistance. The constant and uniform heater temperature over the heater area offers to identify the change in resistance. Therefore, the characteristics of the semiconductor gas sensors like sensitivity, selectivity and the response time are depending on the sensing layer element and the micro heater operating temperature [20]. In sensing layer, the gas chemical reaction occurs at high temperature therefore it is necessary to use micro heater in gas sensors.

Selection of the heating element is important in fabrication of micro heater. For the fabrication of micro heater generally used platinum or poly silicon as heating material and also electrode is used to observe the particular ambient temperature. High resistivity, high thermal conductivity and low thermal expansion coefficient are the important factors in design of micro heaters. Invar is also used as a heating element but the resistivity of this material is very low of order 80x10-8m therefore in order to serve the required purpose longer heater is required. This problem can be overcome by using the heating element INVAR with high resistivity and which is an alloy of Fe, Ni and Co with one hand high resistivity of 80x10-8m and high yield stress and low thermal expansion coefficient on the other hand. Low thermal expansion coefficient (3.4 x 10-6/K) of this material leads to the low thermal deformation of the material and also induces lower stress compared to Ni. The thermal conductivity of this material (10.4) is also almost five times less than Ni, therefore conduction loss is very small for this material and localized heating can be achieved [8]. Furthermore, reduction of power consumption can be achieved by "pulsed heating" mode of micro-heater-based sensors which occurs when the sensor is heated for a short period during measurement. The design and fabrication of a new generation of SMO gas sensors consists of low power consumption MEMS micro-heaters and pulse heating operation, results in very low average power consumption in the range of micro watts. The fabrication process is fully compatible with the commercialized Poly-MUMPs® process, facilitating the integration with other types of MEMS sensors and actuators for low cost, mass production and mobile applications.

The measurement of flow rate of gases plays an important role in the chemical process industries (CPI) and required in many functional applications including safety, process control, product quality, production efficiency, environmental compliance and costs. The inaccurate or inconsistent measurement of the air or other gases leads to the serious accidents, emergency shutdowns, unplanned maintenance, production slowdowns or cost overruns. Today there are six to eight gas flow measurements technologies are available, but only few are suitable for the heavy-duty metering applications which available in the most challenging CPI operations. Each gas flow measurement technology has its own advantages and limitations, depending upon what material to be measured, required accuracy, where it need be measured and so on. There are two types of basic flow meters are available: liquid and gas. Liquid is measured with respect to volumetric flow rate. Gases having unique properties compared to liquids therefore the gas is measured in terms of mass-flow measurement. Some of the volumetric technologies can used to measure the gas flow rate but leads to the problem with totalized flow therefore in critical application the mass-flow measurement technology is the best choice in measuring the air or other gases. Calibration is the method of selecting the proper sensing technology in order to measure flow accurately. There are two methods namely; direct method and air equivalency methods are applied in the calibrating gas flow meter. In direct method the meter is calibrated to a specific pure process gas or to the actual components of a mixed gas in use and in air equivalency method the meter is calibrated using air, and then the calibration is adjusted with a pre-defined correction factor [23]. Considering the significance of a gas sensor, a number of researches have been made; however, realizing the operating environment such as complex gases, operating temperature etc, it always remains an open research region for scholars. As already stated, the factors like substrate materials, filament material, Micro-heater material and design, etc has always the impact on overall sensitivity or performance. Under such circumstances, identifying an optimal material set and design constructs can be of paramount significance for MEMS based gas sensor and flow rate analyzer to be used for industrial or varied purposes. With this motive, this paper mainly discusses some of the key literatures pertaining to MEMS based gas sensor design.

The remaining sections of the presented manuscript are divided as follows. Section II discusses the key literatures pertaining to MEMS based gas sensor designs, Micro-heater design for gas sensor etc. The overall conclusion and inferences of this survey are discussed in Section III. References used for this study are given at the end of the manuscript.

Related Work

This section primarily discusses some of the key literatures pertaining to MEMS based micro-heaters and its use for gas flow measurement. Additionally, the key researches addressing gas MEMS based gas-sensors are discussed in this section.

In the last few years the significant development of electronics, software and hardware technologies have broadened the horizon for industries to exploit them together for better decision making and allied purposes. MEMS can be one of the vital examples which has been playing decisive role across industries. MEMS technology has been used extensively for application like gas sensing, wind-sensing [9], humidity sensing [10], industrial monitoring and control etc. Since, this study primarily focuses on assessing efficacy of MEMS based gas sensors; we discuss different associated technologies [9]. Being low cost solution, MEMS based gas sensors have been increasing exponentially due to low cost, sensitivity, reliability and power efficiency. Amongst the major MEMS based gas-sensing solutions, MEMS micro-heater that emits heat when current is applied to the resistors has gained wide-spread attention. MEMS micro-heater has the key advantage over other state-of-art solutions [10] due to its low power and a very short response time functional ability. Such robustness makes MEMS micro-heaters to play vital role in portable electronics applications which uses low voltage and low power designs [11]. Functionally, heating layer of the Micro-heaters has the vital impact on overall sensitivity and hence selection of the optimal coating material is of paramount significance [9] [11-17]. Researches have been done to design a micro-heaters with SiC [11], Pt [9][12-14], poly-Sic [15], single crystal silicon [16] and TiN [17] as heating layer. A well elaborated discussion of the temperature distribution uniformity on the heating plate of the Micro-heater with heat distribution control can be found in [18]. Also polymide [12] and SOI [20] were used as membrane materials to design Micro-heater based gas-sensors. To enhance sensitivity and reduce false alarm issues, Micro heater has been employed as a hot plate in semiconductor gas sensor [12-14][20][21] in order to control the temperature of the sensing layer. Recently, authors [6] found that the Poly-silicon based Micro-heater design with Finite Element Method (FEM) of COSMOL Multi-physics can enable better temperature uniformity for square geometry sensing unit [9]. However, the predominant limitation of such (poly-silicon) Micro-heater is its long term drift of electrical resistance that often takes place or emerges at high resistance regime. However as solution to the above stated problem, authors [10] found that employing metals allow like Fe, Ni, Co (alloys) can be of paramount significance way to reduce the long term electrical drift, simulating various shapes of micro-heaters achieves better and stable temperature uniformity for all the geometries and is achieved using Deliver Pt (which is made of alloy of Ni, Co, Fe) material for micro-heaters [10]. Long term drift of electrical resistance which occurs at high resistance regime is the major drawback of poly-silicon. To alleviate this problem, authors [50] proposed a Micro heater using a Fe, Ni, Co alloy (Invar) having lower thermal expansion coefficient (~3×10-6/°C) and thermal conductivity (~10.4W/M-K) and high resistivity (~80×10-8Ωm). As already stated in previous discussion, MEMS technology has gained wide-spread popularity for gas sensors applications due to its minimal power consumption, ruggedness, and very minute dimensions. As solution, MEMS Micro-heaters too have gained extensive employability for gas-sensing purposes [24]. Among various technologies used in chemical sensing, SOI (Silicon-On-Insulator)-CMOS based single crystal silicon micro-heaters offer low unit cost, and excellent thermal stability. However, SOI-CMOS sensors generally operate at a temperature of 500^0C, which requires more power consumption for the process [24].

Authors [24] focused on enhancing sensitivity and power exhaustion by using Acetone Sensor based on MEMS Integrated MoO3 Nanostructure. Authors applied fabricated chip Ni heater configuration and standard Reactive Ion Etching (RIE) to design sensor unit [24]. However, SMO sensors operate at high temperature that enables it to be used optimally even at the reduced power consumption. With similar motive, authors [25] design Integrated Gas Sensor (IGS) by using Micro-machined SMO sensors and optimized Micro heaters. FEM concept was applied in [26] to design a robust micro-heater where they applied a thermal induced stress on membrane in integrated gas sensor. This approach enabled [25] achieving reduced power consumption and higher sensitivity. Similarly authors [27] applied Electro-Thermal Analysis (ETA) method to design a Micro-heater based for gas sensors by meander micro heater based on platinum material. Authors found their model efficient towards power efficiency and temperature distribution. In [28] authors used a MEMS design and simulation software Convertor-WareTM and performed ETA over MEMS based Micro-hotplate for gas sensing. This approach was found efficient for reducing sensor-size and surface dimension which eventually yielded power efficiency. Authors [29] considered high temperature gas sensing environment and designed suspended micro-hotplate device which was evaluated using $BaSnO_3$ under O_2 and CO atmosphere. Authors found their design efficient thus helping temperature uniformity and power efficiency. Similarly, authors [30] designed a chemical sensor using Micro-hotplates by using ETA with standard multi user MEMS fabrication process in multi product wafer run. Considering an optimized heater structure goal, author found their model achieving enhanced performance at temperature homogeneity, power consumption and thermal isolation.

In [31], authors focussed on retaining higher sensitivity of the sensor and designed a gas sensor by applying selective nano material of small size and reduced cost, reduce power consumption. Authors applied Tungsten oxide nano-particles network which was heated with the help of on-chip micro hotplate. Similarly, to achieve low power consumption authors [32] applied carbon-MEMS based wafer level batch fabrication sensing platform. Their designed model was a gas sensor with suspended carbon nano wire heater. Similarly, Micro-heater and ink jetting technique were applied in [33] to design a micro C_2H_5OH gas sensor which employed two types of semi-circled heaters by Silicon etching. This method enabled achieving low power solution and even maintained stable thermal uniformity. In [34] authors focused on maintaining stable power consumption using the plasma reactor which is of high density for developing suspended porous silicon (PS) micro hotplates. It was achieved by means of isotropic etching of silicon in PS layer. Authors [35] designed a micro-hotplate on the basis of MEMS standard to be operated at high temperature. In their proposed model, Micro-hotplates (MHP) encompassed electro-thermo-mechanical behavior which was exploited further to perform gas detection. Author [35] applied Coventor-Ware software is used to develop the micro-hotplate and temperature uniformity is enhanced on MHP membrane as compared with absence of SiC in membrane. Similarly, authors in [36] applied Convetor-Ware software to analyze the effect of heater geometry on MEMS micro-hotplates at high temperature distribution. To achieve a solution, authors proposed modification of Micro-heater geometry to enhance heat uniformity so as to make it effective and practical. Considering high temperature gas sensing environment, authors [37] proposed a micro-machined resistive Micro-heater which was found effective in achieving reliable performance at high temperature even at the reduced power consumption and better thermal uniformity. Authors designed a Wheatstone-bridge type resistive Pt heating and multi-ringed heat spreading structures to enhance the thermal uniformity. Similarly, to maintain temperature uniformity authors [38] employed two techniques, laser milling and conductive ceramic to propose a new technology called Ceramic Micro Heater (CMH). In [39] a Molybdenum Micro-Heater (MMH) which is applicable for MEMS-based gas sensor was developed. It was found to be more stable under varying temperature conditions without the resistance drift. To achieve cost-efficient and power-efficient gas sensors, authors [40] designed a poly-silicon micro hot-wire flow sensor. To synthesize it, authors applied commercial 0.35μm 2P4M CMOS technology which was followed by post-CMOS processing. Additionally they applied different flow rates to characterize the fabricated flow sensor. To accomplish a better homogeneous temperature distribution and low power consuming gas sensor, authors in [41] applied thermoelectric micro gas sensor with ligand linked Pt nano particles as catalyst that gave rise to a catalytic Micro Gas Sensor. For MEMS based gas sensor application authors [42] applied ETA to design Micro Heater using a Nickel (Ni) metal. Similarly for thin-film gas sensors with microelectronic technology authors [43] proposed a substrate which describes a laboratory model of substrate for a gas sensor based on semiconducting Tin oxide.

An integrated CMOS MEMS technique was developed in [44] to design a flow sensor by means of compact System on Chip (SoC) to convert flow sensor a low powered such that it can sense bidirectional N2 gas flow. The combination of two wafers by means of proprietary InvenSense A1N process led achieving Heterogeneous integration. To achieve high temperature and low power consuming gas sensor solution, author [45] developed a SOI CMOS MEMS based thermal conductivity gas sensor. The sensor developed encompassed circular membrane and an embedded tungsten micro-heater. To alleviate the issue of high temperature in thermal chemical vapor deposition for synthesis process was applied in [46] where authors proposed CMOS micro-heater to get out from global heating of the micro-system as well as mechanical integrity which is maintained in the Micro-heater. Similarly, authors [47] developed a tin oxide gas sensor using CMOS micro-hotplates and in-situ processing by using the device composed of a sensing film that is sputter-deposited on a silicon micro-machined hotplate.

Considering the high resistivity, low cost, low temperature properties of Nichrome, authors [49] applied it to design a heater element. Authors found temperature Coefficient of Resistance (TCR) of the thin film of nichrome by depositing two popular Physical Vapour Deposition (PVD) methods like Electron Beam Evaporation and DC Sputtering. To achieve better transmittance and resonance at lower temperature for eventual sensing purpose, authors [49] developed a reconfigurable THz filters. To achieve it, authors employed Frequency Selective Surfaces (FSS) with combination of Vanadium Dioxide (VO_2) Phase Change Materials (PCMs) integrated with micro-heater for THz applications. Considering electrical resistance drift author [51] applied a low-power catalytic gas sensing with highly stable silicon carbide micro heaters to prepare a gas sensor. Authors found that their model can enable low power consumption, lower resistance drift than poly-silicon Micro-heater. Authors in [52] proposed a Micro-heater filament on polyimide membrane for gas sensor applications, to achieve good electrical resistance Micro heater filament which is built with Platinum.

To enhance the sensitivity and selectivity author [53] designed pt/ZnO NO sensor integrated with SiC Micro Heater, the NO sensor with ZnO thin film integrated 3C-SiC Micro heater. Noticeably, authors applied 3C-SiC thin film in harsh environment to assess performance. To achieve better performance in sensitivity and selectivity of a micro-machined gas sensor, authors [54] proposed an embedded micro-heater design for gas sensors. To achieve it, they designed a new four-point probe heating element configuration that functioned in conjunction with the thermal behavior of the analytical model. Emphasizing on the sensors selectivity with respect to structural and electrical properties of Micro heater author [55] introduced thermal annealing treatment process in nitrogen atmosphere. This was done at 450°C temperature and continued for 30 minutes. Authors applied Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) to assess properties. With similar motive authors [56] applied COMSOL to design a Micro-hotplate for the MEMS based gas sensor, where authors applied FEM to assess high temperature uniformity. To provide ultra-low power consumption, high sensitivity, low noise, low unit cost, reproducibility and reliability, authors [57] designed SOI CMOS micro-hotplates gas sensors. In this design solid state gas sensors were embedded in SOI micro-hotplates on a SOI membrane applying MOSFET heaters. To achieve better linearity and sensitivity, in [58] authors applied used miniaturized chemical sensors to design a Batch fabrication model for metal oxide sensors on the micro-hotplates. To achieve it, authors performed direct integration of nano structured transition metal oxide films onto micro-hotplates on the basis of the micro-machined suspended membranes. Similarly, in [59] authors considered high-speed micro gas chromatography (muGC) and proposed micro-fabricated silicon-glass separation columns which were integrated with resistive heaters, temperature and capacitive pressure sensors, low mass columns separate eleven-component gaseous mixtures such as alkanes simulants, TNT, sarin, and mustard gas. To alleviate long response time and achieve high sensitivity, Saremi et al [60] proposed a MEMS-based hot-film thermal anemometer with wide dynamic measurement range using platinum thin film resistors. To enable fast response and higher sensitivity authors [61] implemented a MEMS-based flow sensors based on hot films. Resistors were obtained by the deposition of platinum layer on substrate with the help of MEMS techniques. Here resistors are indicated as heater and sensing element.

To enhance the sensitivity of the sensor, there are two types of mechanism namely, thin film and thick film deposition techniques, which play vital role in formation of sensing layer to attain better gas sensing ability. Considering this fact, to enhance the sensitivity of the sensor the author [62] implemented a structure of an integrated surface micro-machined convex micro hotplate for tin oxide gas sensor array. Moreover to achieve high sensing capacity of the sensors by considering the bidirectional thermal expansion flow the author [63] developed a micro-machined three-axis gas inertial sensor. To achieve thermos-resistive sensing, eight heaters and eight thermistors were used in "cross-shape to obtain the bidirectional thermal expansion flow. Author [64] designed highly accurate MEMS thermal wind sensor, where sensor applied eight central heaters and eight thermistors placed on ceramic substrate. Authors split this model into cross type group and saltire-type group. However the sensors were not immune to external vibration. Emphasizing on these criteria authors [65] designed a MEMS-based coriolis mass flow sensor to be used for industrial application. Applying silicon tubes the micro-machined flow sensors were developed and bonded on to a metalized glass substrate so that the sensors are resistant to the parameters like pressure, temperature, vibration, fluid density, and viscosity. Similarly to enhance sensing capacity for the gas flow measurement model, author [66] developed a smart flow sensor based on MEMS, flow sensor consist of curved-up cantilever beams array with deposition of surface-micro-machined layers. For the purpose of gas sensing in different gas mixtures simultaneously author [67] designed micro-hotplate for MEMS based integrated gas sensing system. Focusing on response time, author [68] developed in-plane capacitive MEMS flow sensor. Considering dynamic pressure, it applied the displacement of a micro-fabricated paddle that led to the measurement of flow velocity of surrounding gas. However, results revealed it to have high response time. To enhance response time and temperature uniformity author [69] designed hotplates with ultra low power consumption by means of metal oxide gas sensor substrates.

Different ULP devices differ in terms of the respective shape and size, especially when fabricated using same front-side bulk silicon micromachining technology. Considering this fact, authors [70] stated that the large displacements produced by vanadium dioxide (VO_2) integrated MEMS based actuators can precisely be controlled by means of a simple proportional-integral-derivative (PID) controller and an integrated heater. To mitigate long-term stability author [71] designed a new concept applying MEMS heater that achieved broadband wavelength infrared light source. To achieve it, authors applied SOI technology and SOI wafer which have low electrical resistance. To achieve better system performance like ultra-low power consumption, low unit cost and better thermal stability authors [72] proposed a SOI-CMOS based single crystal silicon micro-heater. Authors applied SOI-CMOS method with deep RIE back-etching to enable gas sensing. Considering the chemical sensor array to be used in oil factory authors [73] designed chemical micro sensors by employing CMOS integrated MEMS sensitive layer coating of CMOS cantilever beams. Authors found that their model can function in resonant, swelling or calorimetric modes. To reduce power consumption and better thermal performance author [74] designed SnO2 chemical sensor by employing coupled electro-thermal simulation software (SESES™). In [75] authors developed a method for the integration of a multiwall carbon nano tubes film using MEMS so as to design the chemical sensor setup. Authors developed MEMS based Micro Heaters to be used as temperature heating unit as well as pulse heating source. In [76] authors made effort to integrate sensor structure and TiO thin film deposition to design a gas sensor model. Authors employed AAO method for developing nano-porous gas sensors as this approach ensures reduction of complexity of conventional surface poration process. To enable fluid flow control from micro valve diaphragm, Vandelli et al [77] implemented a micro valve array comprising parallel array of surface-micro-machined binary micro valve. Similarly, employing the concept of thermo-pneumatic actuation author [78] proposed a micro-fabricated valve for industrial gas and liquid flow sensing detection. In [79] a localized laser bonding technique was developed for ceramic MEMS packaging so as to detect the laser power density and scanning speed. To assess physical realization, authors applied FEA thermal model that examined localized laser bonding process. To achieve high thermal resistance isolation structure authors [80] designed an oxide refill process that enabled retrieving first-order Temperature Coefficient of Frequency (TCF) of silicon MEMS resonators to null. However author failed addressing the key parameters such as low frequency drift and large temperature dependency.

Employing MEMS technology authors in [81] designed micro thermal bubble actuators. Authors failed to address the performance of frequency response, flow rate and discharge pressure. Noticeably, the results show that proper consideration on heater geometry play a vital role in utilization of heater as a thermal actuator. To enable complete transient flow solution, authors [82] designed a simulation based model with fluidic gyroscope sensor based on triple axis MEMS. To confine the effect of acceleration and gravity on measurement of rotation author [83] applied the thermal MEMS gyroscope which is of smaller gyro with shorter heater switching frequency leads to drain in spurious signal. Authors [84] developed a tin oxide gas sensor to detect the complex odors. To achieve it the sensor heater employed high magnitude voltage impulses of predetermined thermal impacts. Authors [85-89] designed a micro heater with resistive filaments made of heating materials namely titanium, platinum, molybdenum, tungsten, or poly-silicon miniaturized to ~100nm to ~100μm using MEMS fabrication techniques. Authors declared their model to be low power, swift responsive, and better in mechanical stability features. Micro-heaters [85] were applied for the application of micro-ignition for micro-propulsion systems and micro-explosive boiling. Micro heaters are also used in both 2D and 3D printing systems such as inkjet printing [90] [91], thermal printing in a point-of-sale (POS) printer [92] and selective heat sintering (SHS) [93]. Here micro-heaters were able to functional effectively at the temperature of 300°C. Though, numerous literatures have been studied to explore Micro heaters based gas sensing design, research still hopes better solution. For example, glass and silicon has been examined to be applied in Micro heaters, where Glass gains preference due to its low thermal conductivity, while silicon gains place due to ease of processing with MEMS fabrication. To enhance the power efficiency authors [94] used the silicon for the micro heater, which it was etched away to leave the micro heater a thin membrane of dielectric material to make sensing better. Authors [95][96] introduced the design process flow to fabricate a heater with MEMS techniques using dielectric layer. To design the model, authors applied photolithography to pattern the substrate and then deposited the micro heater material followed by conductive leads with sputtering or e-beam evaporation.

Literatures reveal that in Micro heater designing it is important to consider the characteristics like heat transfer, geometry and thermal response time, which could not be addressed in their study. As stated, functionally, Micro heaters transfer the heat in three modes such as conduction, convention and radiation. At temperature less than ~700°C the conduction mode and convention mode are significant, while radiation is insignificant for Ti or Pt micro heaters [92][97][98], and therefore the selection of materials and temperature sensitiveness is of vital significance. In [86], authors applied numerical simulation to select material by calculating maximum temperature and power savings using different insulating layers. With similar effort authors [99-101] focussed on enhancing the geometries so as to achieve power savings, reduce- stress profiles and efficient heat distribution. Emphasizing on operation of micro heater, especially to enhance the thermal response time authors [88] proposed tungsten micro heaters that enabled achieving thermal response time up to 2 ms at the temperature of 600°C. It was found exhibiting the power consumption of 12mW. Author [94] applied Pt/Ti as material to design Micro heater so as to achieve thermal response time of 1ms with temperature of 400°C using only 9mW of power, but they are not optimized for even temperature distribution. In practice even MEMS packaging material too has impact on overall sensing efficiency. Considering this fact, authors [102][103] selected packaging materials for a MEMS device in such manner that it could withstand the operating condition such as high temperature operation, high pressure, chemical resistance, mechanical and thermal shock and vibration. As solution, the most commonly used materials for micro heater packagings are metals, ceramics, silicon and plastics. Authors [104] concluded that Metals are good for their robustness ease of assembly, mechanical integrity and chemical inertness in harsh environments and ceramics are good for their material properties like electrically insulating, hermetic sealing, thermal conductivity and chemical inertness and to the ease in shaping. However, very few researches have been reported on micro-heater packaging. Considering structural optimization the fact that the Micro heater is a small resistance heater and it operates by passing an electric current across a filament to generate heat, is needed to be considered. Since the response time of the micro heater is very fast, a sophisticated feedback system is used to control the temperature. The authors [105] [106] applied Proportional-integral derivative (PID) controls in order to control the temperature of the micro heater. Similarly feedback control for a micro heater in which the resistance of a conductor changes with its temperature; thus, the average temperature of some conductor may be determined through its change in resistance [107]. The temperature of the micro heater is usually read through the resistance change of an additional metal filament which is near the micro heater, rather than by reading the resistance of the micro heater [106] [107]. A snippet of the different researches made and their methodological paradigm and goals are depicted in Table I.

Table I Different researches and associated methodological paradigms

Author	Model	Material used	Purpose
Mailly et al. [9]	Micro- heater	Pt as heating layer	To achieve low power consumption
Chen et al [11]	Micro- heater	SiC as heating layer	To achieve low power consumption
Das et al [15]	Micro- heater	Poly-Sic as heating layer	To achieve low power consumption
Furjes et al [16]	Micro- heater	Single crystal silicon as heating layer	To achieve low power consumption
Creemer et al [17]	Micro- heater	TiN as heating layer	To achieve low power consumption
Aslam et al [12]	Micro- heater	Polymide as membrane materials	To control the temperature of the sensing layer
Partridge et al [20]	Micro- heater	SOI as membrane materials	To control the temperature of the sensing layer
Bedoui et al [27]	Micro- heater	Platinum	To accomplish low Power consumption and temperature distribution
Moon et al [33]	Micro- heater with ink jetting technique	Si	To establish low power consumption and also maintains the stable thermal uniformity
Lee et al [37]	Micro-machined resistive Micro- heater	Pt	accomplish high temperature, low power consumption and good thermal uniformity
Moldovan et al [38]	Used laser milling and conductive ceramic technology to develop Ceramic Micro-heater		To maintain temperature uniformity
Rajeswara Rao et al [39]	Molybdenum Micro- heater based on MEMS technology		To obtain stable temperature without considering the resistance drift
Miao et al [40]	Developed polysilicon Micro- hot-wire flow using commercial 0.35µm 2P4M CMOS technology	Nickel	To confine the cost as well as power consumption
Roy et al [42]	Micro- heater		To design a low cost gas sensor solution
Ahmed et al [44]	CMOS MEMS flow sensor		To achieve low powered solution
Sarfraz et al [45]	SOI CMOS MEMS based thermal conductivity gas sensor with Micro- heater		To achieve high temperature and low powered solution
Suehle et al [47]	CMOS Micro- hotplates gas sensor	Silicon	
Das et al [48]	Proposed temperature Coefficient of Resistance (TCR) with PVD	Nichrome	
Modal et al [50]	Micro- heater	Fe, Ni, Co alloy (Invar)	To achieve lower thermal expansion coefficient and thermal conductivity and high resistivity for critical gas sensing application under complex gas environment
Harley et al [51]	Micro heater sensor	Silicon Carbide	provides low power consumption, lower resistance drift than polysilicon microheater
Noor et al [52]	Micro- heater	Platinum	to achieve good electrical resistance
Shim et al [53]	pt/ZnO NO sensor integrated with Sic Micro- heater	Sic	To enhance the sensitivity and selectivity
Hamid et al [55]	Developed microheater with SEM and AFM		To enhance the selectivity
Joy et al [56]	Developed Micro- hotplates for gas sensor with FEA using COMSOL Multiphysics tool		To obtain high temperature uniformity
Udrea et al [57]	SOI CMOS Micro- hotplates gas sensors using MOSFET heaters		To provide ultra-low power consumption, high sensitivity, low noise, low unit cost, reproducibility and reliability
Saremi et al [60]	MEMS-based hot-film thermal anemometer	Platinum	To alleviate long response time and consequently achieve high sensitivity
Wang et al [61]	MEMS-based flow sensors based on hot films	Platinum	To achieve fast response and higher sensitivity

Guo et al [62]	integrated surface micro-machined convex micro hotplate		To enhance the sensitivity
Chang et al [63]	micro-machined three-axis gas inertial sensor		To achieve high sensing capacity and to achieve thermos-resistive sensing, eight heaters and eight thermistors are used in “cross-shape” in order to obtain the bidirectional thermal expansion flow
Smith et al [65]	MEMS-based coriolis mass flow sensor	Silicon	To design sensors as resistant to the parameters like pressure, temperature, vibration, fluid density, and viscosity
Nguyen et al [68]	in-plane capacitive MEMS flow sensor		To enhance the response time
Elmi et al [69]	Hotplates using metal oxide gas sensor substrates	Silicon	To enhance performance of response time and temperature uniformity
Iwaki et al [72]	SOI-CMOS based single crystal silicon Micro-heater	Silicon	To design a ultra-low power consumption, low unit cost and excellent thermal stability
Wei et al [75]	MEMS based micro heaters	Carbon	used as temperature heating unit as well as pulse heating source
Vandelli et al [77]	Micro- valve array		To achieve fluid flow control from the effect of micro valve diaphragm complains
authors [85-89]	Micro- heater	Titanium, Platinum, Molybdenum, Tungsten, or Polysilicon	To achieve low power consumption, fast response, good mechanical stability
Xu et al [94]	Micro- heater	Pt/Ti heater and Silicon underneath the Micro- heater	To enhance the power efficiency, to achieve thermal response time of 1ms with temperature of 400°C using only 9mW of power

CONCLUSION:

The exponential rise in technologies have broadened the horizon for research and scientific community to enable a more efficient and adaptive technology to cope up with default and complex work environment. The development in hardware technologies, material sciences, etc have given rise to a new horizon where research community intending to enable environmental sensitive gas detection and control so as to avoid any hazardous consequences. There are different application environment such as manufacturing setup, strategic infrastructures, etc where sensing dynamic parameters such as temperature gas concentration, type of gas and its associated hazardous level is must. Towards this objective, numerous researches have been done, which has gained widespread attention due to increase in MEMS technologies. Though, the use of MEMS makes sensing and control or actuation more precise and efficient, designing sensor model is often a challenging task which must be optimal as per application environment, complexity or nature of gas and its composition etc. Realizing this fact as motivation, this study primarily made effort on studying and exploring different MEMS based gas sensor design, where different approaches such as Micro-Heaters based solutions have been studied. Since gas sensing is always depending on the selection of materials and operating environment, the focus is made on identifying suitable materials to design Micro-heaters for gas sensing purpose. This study revealed that majority of the researches have made effort to design micro-heaters using SiC, Pt, poly-Sic, Nickel, single crystal silicon, TiN etc as heating layer. Study revealed that the polymide and SOI can also be applied as membrane materials to enhance the sensitivity and to reduce power consumption. Studies reveal that undeniably Micro heater can be applied as a hot plate in semiconductor gas sensor which can enable controlling the temperature of the sensing layer and hence can make detection more precise and sensitive. As enhanced solution, MEMS Micro heaters can be augmented with pulse heating operation which can reduce power consumption. Practically, the interface of enhanced (material enhancement as well as structural enhancement) with MEMS sensors and actuators can enable low-cost solution to meet up surging demands.

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