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Thermal Analysis of Greenhouse Gases Using MEMS Based Platinum Micro heater

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ABSTRACT

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Insemiconductorbasedchemicalsensors,themicroheaterofaMicroElectromechanicalSystemiscrucial. TheCleWinmaskdesigningtoolisusedtodesignaplatinum-basedmicroheater,whichisthenfabricatedusingthesurfacemicromachining technique. The temperature sensor is integrated with the developed platinum microheater to analyze thermalactivity. Using revolutionary research equipment called sensimer, a thermal analysis such as the rising time and fall time of theheater is performed on the $CO_2$and CH_4 selected greenhouse gases. The fabricated microheater with an integrated temperaturesensorshowsagoodresponsetowardstheabove-mentionedgasesandconsumeslesspower.Thetemperatureofthemicroheateris varied from 30°C to 400°C and then analyzed its performance. From the experimental analysis, we can observe that the powerconsumed and the average pulsing time constant of the microheater for CO_2 gas are 2.8mW and 6ms and for CH_4 gas are 3.6mWand5msrespectively.Inthisstudy,thethermalanalysisoftheabove-mentionedgreenhousegascausing materialsisdescribed.

IndexTerms–Greenhousegases,MEMS,Microheater,Sensimer,Thermalanalysis.

I. INTRODUCTION

Increased industrialization has undoubtedly helped many countries economic prosperity, but it has also resulted in a significant risein poisonous gas and other severe environmental pollution emissions. As a result, accurate monitoring of dangerous gases andpollutant detection in the environment has become an inevitable concern in recent years. In this environment, designing robust,low-cost, and portable chemical sensors is required to build a new range of chemical sensors with higher sensitivity. Sensors aredevicesthatconvertphysicaleventsintodatathatcanberead.Mechanical,electrical, optical,andmagnetictypesareavailable.

Various MEMS-based chemical sensors, each operating on distinct criteriasuch as capacitive, thermal, resistive, and so on,are widely used in the detection of harmful gases. These sensors, which can range in size from a few micrometres to a fewcentimetres, are produced utilising Integrated Circuit (IC) batch processing processes. On the micro-scale, these sensors can sense,control, and actuate, and on the macro size, they can cause effects. Gas detection sensorsare designed to keep the concentrationsofcertaindangerousgaseswithinasafe limit.

A chemical sensor is made up of a transducer and an active layer that converts chemical data into electrical signals such asfrequency, current, and voltage changes. Catalytic sensors, thermal conductivity gas sensors, electrochemical gas sensors, opticalgas sensors, infrared gas sensors, semiconductor metal oxide sensors, and acoustic wave gas sensors are some of the gas detectingtechnologies used to detect harmful gases [1]. Metal Oxide Semiconductors (MOS) are one of these technologies that play acritical role in the detection of target gas concentrations. The development of MEMS chemical sensors based on metal oxidesemiconductortechnologyisthetopicofthisresearch.Figure1depictsthefundamentalstructureofaMOSsensor.A MOSsensorismade upofthe keylayerslistedbelow.

a) Siliconwaferasa substrate
b) Insulatingmaterial
c) Microheater
d) Interdigitatedelectrodesand
e) Sensingfilm

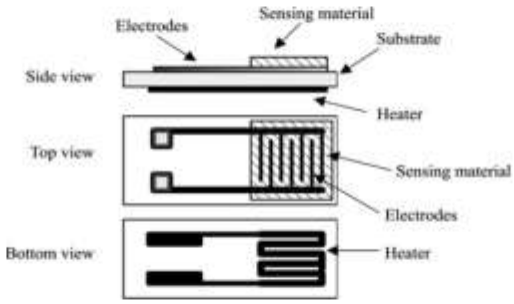


FIGURE1:STRUCTUREOFMOSSENSOR

The bottom layer is the substrate, which serves as a foundation for the heater. Silicon is the most used substrate due to itsconsistent mechanical characteristics. The layer between the substrate and the microheater is known as the insulating platform. Aninsulating platform is utilised to prevent direct damage to the substrate as well as to limit heat loss. Microheaters are employed inmetaloxidegassensorsto properlydetectthetargetgas.Theheatingofthemicroheater isdoneusingjoulesof heat.
Under the sensing layer, integrated electrodes are utilised to determine fluctuations in the resistance of the metal oxide sensorsurface as it responds to gases. When the gas is absorbed into the layer, the integration is nothing more than a digit-like pattern ofelectrodes employed in resistance or capacitance measurement. When the sensor is exposed to air pollutants, the conductivity ofthe material changes. Integrated chemical sensors are quite popular due to their low cost. Metal oxide sensing layers can be madeout of a variety of materials depending on the gas being felt, and they have a high sensitivity to dangerous gases. The conductivityofthislayervariesdependingontheamountofgaspresent.
The oxidation or reduction process on the detecting layer of metal oxide sensors occurs at a certain temperature. The numberof free electrons on the layer is determined by oxidation or reduction, which increases or decreases the conductivity of the layer.The microheater is crucial in attaining the correct temperature for the reaction. In the design of a microheater, criteria such ashomogeneousheating, lowpowerconsumption, andmechanical stabilitymustbe considered.
When designing microheaters, it is necessary to consider issues such as heat transfer, form, and thermal reaction time, whichwere not addressed in their work, according to the literature. As previously stated, microheaters transport heat in three ways:conduction,convention,andradiation.For Ti orPtmicroheaters,theconductionandconventionmodesaresubstantialattemperatures less than 700°C, whereas radiation is minor [2], therefore material selection and temperature sensitivity are critical.The authors used numerical simulation to determine the best material by estimating the greatest temperature and power savingsfrom various insulating layers [3]. Authors devoted similar effort to improving microheater designs in order to obtain powerreductions,lowerstressprofiles, and effective heatdistribution[4].
The authors presented tungsten (W) microheaters with thermal response times of up to 2ms at 600°C, focusing on microheateroperation. It was discovered to have a power consumption of 12mW [5]. The authors designed a microheaterutilisingPt/Ti as amaterial and achieved a thermal reaction time of 1ms at 400°C with just 9mW of power, despite the fact that they were not tunedfor even temperature distribution [6]. The material utilised in MEMS packaging has an impact on total sensing efficiency inpractice.
As a result, the author selected packaging materials for a MEMS device that could survive operational circumstances such ashigh temperature, high pressure, chemical resistance, mechanical and thermal shock, and vibration. Metals, ceramics, silicon, andplastics are the most often utilised materials for micro heater packaging [7]. Metals are good for their robustness, ease of assembly,mechanical integrity, and chemical inertness in severe settings, while ceramics are good for electrically insulating, hermeticsealing,thermalconductivity, chemical inertness,andease ofshape[8].
Microheater packaging, on the other hand, has gotten a lot of attention. When contemplating structural optimization, it'simportant to remember that themicroheater is a small resistance heater thatgeneratesheat by delivering an electric currentthroughafilament.Thetemperatureisadjustedviaasophisticatedfeedbackmechanismbecausethemicroheater's responsetimeissoshort.Tocontrolthetemperatureofthemicroheater,theauthors usedProportionalIntegralDerivative(PID)controllers[9].
Similarly, feedback control for a microheater in which a conductor's resistance changes with its temperature; hence, theaverage temperature of a conductor can be calculated by its resistance change [10]. Rather than reading the resistance of themicroheater, the temperature of the microheater is commonly determined by the resistance change of an extra metal filamentlocatednearthemicroheater[11].Differentresearchersusedvarioustypesofmicroheaters.Table1displaysthefindingsofastudyofdifferentresearchersmicroheaters,aswellasthetemperatureachieved

fortheamountofelectricity,used [12,13].

As previously stated, substrate materials, filament material, micro-heater material and design, among other things, all have animpact on overall sensitivity or performance. In such cases, determining the best material set and design structures for a MEMS-based gas sensor and flow rate analyzer that will be used for industrial or other purposes is critical. This research focuses on thethermal analysis of greenhouse gases $CO_2$and CH_4using the Labyrinth, a unique microheater structure that can produce highertemperaturesthanpreviousmicroheaterdesignsfor CO_2andCH_4thermal research.

TABLE1
SURVEYONMICROHEATERSGEOMETRYANDTHEIRPOWERCONSUMPTION[12,13]

Designgeometry	Averagetemperatureachieved (^{o}c)	Powerconsumption (mW)
Doublespiral	375.65	2.2
Meander	330.9	2.9
Sshape	380.7	3.6
Fan	372.7	2.7
Hilbertorder3	376.21	3.6
Hilbertorder4	360.78	3.9
Mooreorder 3	376.66	2.5
Moore order4	361.66	2.0
Peanoorder2	379.57	3.8
Peanoorder3	317.38	2.9

DESIGNAND FABRICATIONOFMICROHEATER

The performance of semiconductor metal oxide gas sensors is determined by the operating temperature of the sensing layer. Theoperation temperature for various target gases affects the redox processes and response rates on the surface of the sensor film.Because electrical features such as changes in resistance or capacitance of the sensing film require a high temperature to detect,microheaters are a keycomponentinmetal oxide semiconductor gassensors.

Microheaters must have strong heat confinement, high stability, high manufacturing yield, and low power consumption inorder to manage temperature distribution along the active region. A suitable microheater shape must be chosen to meet theaforementioned specifications, and the heater's performance can be increased by selecting an optimal high resistive material.Spiral, meander, double meander, and double spiral are the most common microheater structures. The active area temperatureremains a hurdle to gas sensor performance, despite the fact that these structures provide average temperature uniformity over thedetecting region [14]. We developed, simulated, and analysed three different metals for the proposed MEMS based microheaterdesigntoaddressthese challenges,withthegoalofimprovinglowpowerand temperatureuniformity.

CleWin 4.1 was used to design the suggested microheater. The heater geometry of a metal oxide semiconductor sensor mustbe carefully engineered to provide the desired temperature uniformity and overall performance. As a result, the shape of theheating element and the material used to heat it must be carefully determined. Using a high thermal conductivity material,temperature consistency can be attained throughout the heater area [15]. Three different conductive metals, such as Platinum,Titanium,andTungsten, areusedasheatingelementswitha thicknessof100nm.

To minimise conduction losses, a very thin (20nm) silicon dioxide membrane of size 100µX100µm is used as a high-temperature electrical insulator that supports the heating film [16]. The performance of the heater is directly influenced by theelectrical insulators [17]. Good consistency and the required operating temperature disclose theuse of heater material. Theproposed microheater Labyrinth geometry pattern is shown in Figure 2, and the design geometry dimensions are included in Table2.

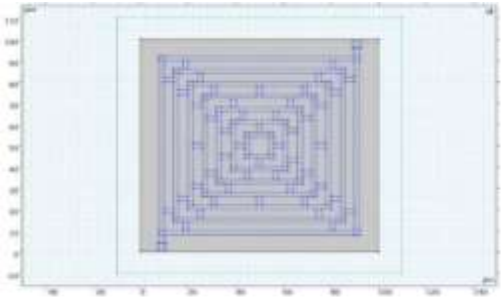


FIGURE 2
LABYRINTHMICROHEATERDESIGNGEOMETRY

TABLE2
DIMENSIONSOFTHEMICROHEATER DESIGN

Materialsused	Pt/Ti/W
Area	100*100 µm
Thickness	100 nm
Width	2.5 µm
Fingergap	5 µm

Platinum is a precious metal that has low density, high thermal capacity, and high electrical conductivity, making it one of therare elements found in the earth's crust. Because of its high melting point, it has good thermal stability, allowing it to tolerate hightemperatures and reach the highest temperature for the smallest voltage. Tungsten (W) is a high-temperature, high-mechanical-strength metal [18].

TABLE3
MATERIALPROPERTIESFORPLATINUM

Parameter	Platinum(Pt)
HeatCapacity[J/kg*K]	133
Young'smodulus(E)[Pa]	168e9
Thermalexpansioncoefficient(α)[1/K]	8.80e-6
Thermalconductivity(k)[W/(m*K)]	71.6
Density(ρv)[kg/m^3]	21450
Electricconductivity(σ)[S/m]	8.9e6
Electricresistivity[Ωm]	3.4e-7

A titanium (Ti) layer is typically used to strengthen the heater's thin film's adherence [19]. Table 3 [20] shows the materialproperties of microheaters. The microheater is designed by utilising the CleWin 4.1 design tool and surface micromachiningprocess.The developed microheater'sschematicgeometricaldetailsareillustratedinFigure 3.

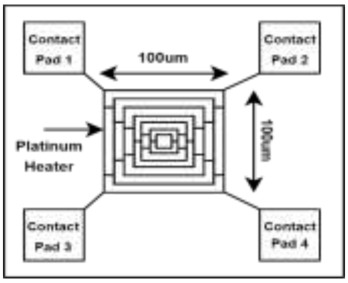


FIGURE 3
SCHEMATICOFPROPOSEDMICROHEATER LABYRINTHDESIGN.

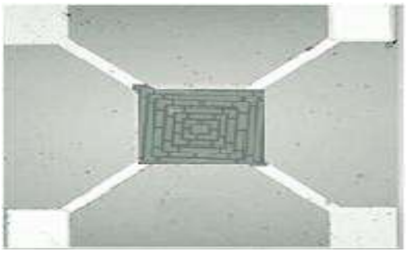
The temperature sensor is built into the planned microheater. As illustrated in Figures 4 (a) & (b), it consists of two suspendedplatinum coils H and H^1 and RTD (temperature sensor) R and R^1 (b). The die surface area of the microheater is 2.5mm * 2.5mm,and the membrane size is 100*100µm. The surface micromachining approach was used to create a simulated MEMS microheaterstructure. RCA1 (Radio Corporation of America standard1) and RCA2 (Radio Corporation of America standard2) protocols areused to clean the silicon substrate. The wafer was incubated in RCA1 solution for 15 minutes at 75°C. RCA1 solution is used toclean thewaferat 75°C for 15 min. The RCA1 and RCA2cleaning protocol solution ratio is taken as H_2O: NH_4OH: H_2O_2:: 10:2:2,and H_2O:HCl:H_2O_2:12:2:2,forHF(Hydrofluoricacid)HF:H_2O::3:12:0 respectivelyforRCA1andRCA2 protocols.

After being treated with RCA1 solution, the silicon wafer is rinsed with distilled water before being treated with RCA2solution to remove any contamination on the wafer surface. The wafer is then placed on a hot plate with a temperature of 270°C toeliminate any remaining fumes. The analytes are then coated thinly on the wafer using the spin coating process. Then, to increasewafer adhesion quality, gentle baking is done by heating the substrate in a furnace to 120°C for 30 minutes. The substrate issubjected toUVlightwithawavelengthof360nmandradiationintensityof40mJ/cm^2 to formpatternpictures.
The produced sensor is now developed for 45 seconds using Tetra Methyl Ammonium Hydroxide (TMAH MF26A) and driedwith nitrogen gas. The substrate is heated at 100°C for 5 minutes to generate a physical mask that surrounds the wafer and protectsit from chemical contamination during etching. To increase the adhesiveness on the wafer surface, the hard baking technique iscarried out aftersoftbaking.
The microheater is now subjected to UV photolithography in order to dry etch the photoresist from the wafer. The wafer isthen installed on an ICPRIE (Inductively Coupled Plasma Receptive Particle Scratching) equipment to do this. In ICPRIE, analuminium nitrate base is used to allow for proper warm vitality exchange between the carrier wafer and the MOS substrates. Thisallows for successful anisotropic etching of the substrate using the Bosch method. Anisotropic carving is done with the gasessulphurhexafluoride(SF_6)andoctaflurocyclobutane(C_4F_8).Table4showsthedetailsoftheparametersusedinICPRIEanisotropicetching.

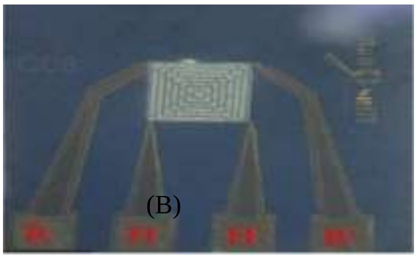
TABLE4
PARAMETERSUSEDINANISOTROPICETCHING

Variables	Specification
Type ofMask	AZ5214
Sulphurhexafluoride(SF_6)	30SCCM
Octaflurocyclobutane(C_4F_8)	70SCCM
InductivelyCoupledPlasma(ICP)power	900W
RadioFrequency(RF)Power	120W
Etchtime	15 sec
Chamberpressure	15mbar
Processtemperature	15°C

After dry etching, the residue of the photoresist is burned by the ICPRIE instrument. To confirm the removal of unwantedsilicon,the opticalmicroscopicinspection wascarried out,wherethechangeincolourofthesubstrateisobserved.



(A)



(B)

FIGURE4
A) MEMSMICROHEATERDESIGNINCLEWINSOFTWAREB)SEMIMAGEOFTHE DESIGNEDMICROHEATER

Thedevelopedsensorasthedieafterthefabricationisshownin Figure 5.

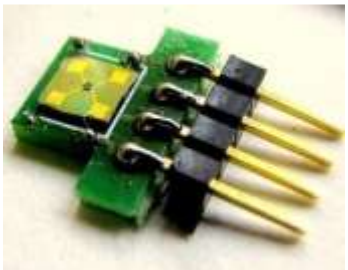


FIGURE5
DEVELOPEDMICROHEATERDIESETAFTER FABRICATIONWITHFOUR PINSR,R1H,H1

EXPERIMENTATION IN SENSIMER

Sensimermicroheater tester is used to test the produced microheater. Sensimer is a microheater testing tool that can be used to dothermal analysis on powder or liquid testing materials. As illustrated in Figure 4, the developed microheater comprises four pins.The sensitive electrodes inside the sensimer receive a sinusoidal voltage input, which causes the temperature of the microheater torise and fall in milliseconds in a pulsating pattern. For all of the investigated materials, the pulse increases and falls times oftemperaturearemeasured.

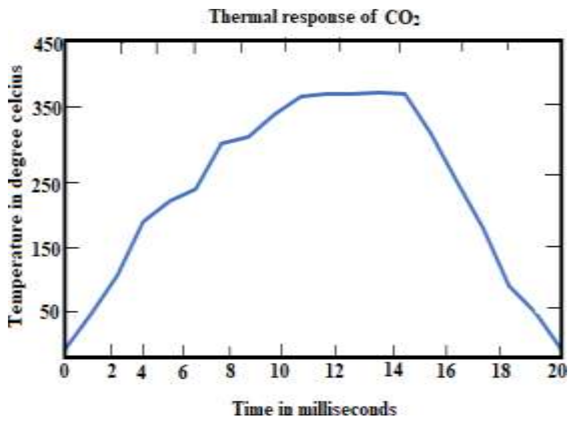
Because each material has a different coefficient of temperature, the rise and fall times of the temperature response arevariable for each material. The rise and fall times of temperature vs. time are studied in the experiment for all of the selectedgreenhouse gases, and the results are provided in the results and discussion section. Figure 6 depicts the device sensimer that wasutilised inthe study.

FIGURE 6
SENSIMERMICROHEATERTESTINGMACHINE

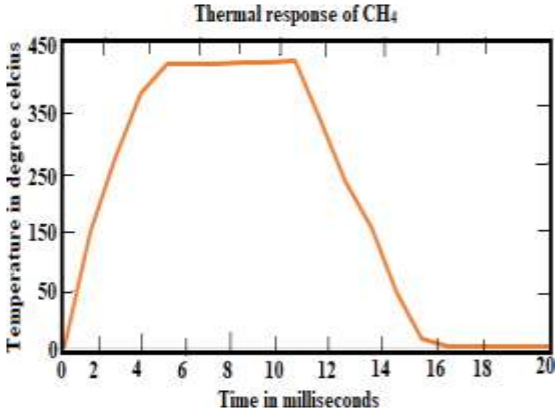
Sensimer is a desktop experimental device that allows you to change the temperature of a microheater in order to study itsthermal response. It is made out of a microheater plug-in port and related electronics, as well as software to control electricalexcitation.Thegraphoftemperaturevs. time depictsthethermalmassresponseofamicroheater foramaterial.

II. RESULTS AND DISCUSSIONS

At the end of the paper, you must include a list of references. If it's not absolutely essential, start them on a new page. Everyreference in the text should also appear in the list of references, and vice versa. In the text, use [1] or [2], [3] to indicate references.In this study, the selected greenhouse gases CO_2 and $CH_4$are tested in powder form in a microheater. The thermal responses of$CO_2$and $CH_4$are evaluated independently, and then the rise and fall times of both thermal mass are compared, in order to studythetemperaturesensitivityof selected greenhousegases.Figure 7 depictsthe thermalreactionofgreenhousegases.



(A)



(B)
FIGURE 7
Thermalresponsegreenhouse gases(A)CO_2(B)CH_4

TherisingperiodofCO2is10ms,andthefalltimeis6ms,accordingtothegraphinFigure7(a).Wemaydeducefromthegrap hinFigure7 (b) that the risingtime ofCH_4is5msand the falltimeis6ms.

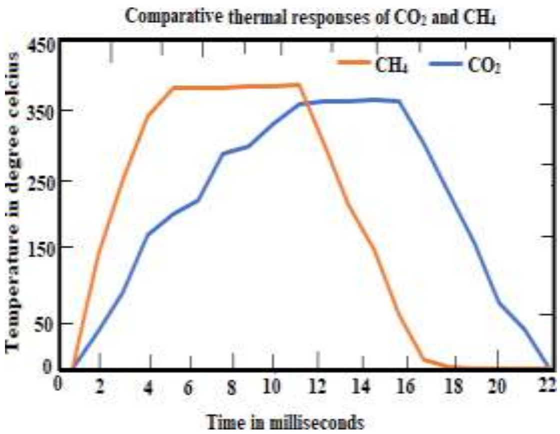


FIGURE8
COMPARISONOFTHERMALRESPONSES OFCO_2ANDCH_4

Figure 8 shows a comparison graph of CO_2 and CH_4 temperature responses, which is summarised in Table 5. Carbon dioxide(CO_2) molecules have a unique property that allows them to absorb energy from infrared (IR) light. The CO_2molecule vibrates asa result of the photon's energy. The molecule subsequently gives up this extra energy by emitting another infrared photon later.Oncetheextra energyisremoved bytheemitted photon, thecarbondioxidemoleculestopsvibrating[21].
CO_2 molecules are often flowing, striking with other gas molecules and transferring energy from one molecule to the next. ACO_2 molecule will most certainly collide with multiple other gas molecules before re-emitting the infrared photon in the morecomplex real-world process. The energy gained from the absorbed photon could be transferred by the CO_2 molecule to anothermolecule, increasing the speed of that molecule's motion. Because the temperature of a gas is proportional to the speed of itsmolecules, the quicker motion of a molecule caused by an IR photon absorbed by a CO_2molecule boosts the temperature of thegas[22].
CO_2requires a high-temperature environment to be detected due to its enhanced heat-absorbing capacity. As a result, amicroheater with a temperature of 390°C was designed to shatter the CO_2 atoms on the sensor, as shown in Figure 7. (a). Whencompared to oxygen and nitrogen, which can break at 60–70°C [23], this is a pretty high temperature. The ability to absorb moreheatincreasesasthe gasconcentrationrises.

Methane, which comprises one carbon atom and four hydrogen atoms, is a more potent gas in the atmosphere than CO_2. Itcontributes more to the greenhouse problem while being present in much fewer quantities than CO_2 [24]. In comparison to CO_2,methane has a very high IR radiation absorption capability, which allows it to store more heat [25]. As a result, breaking the atomsof CH_4required more heat from the microheater than breaking the atoms of CO_2, as illustrated in Figure 7. (b). The CH_4microheater heat was 419°C, while the CO_2 microheater heat was 390°C. A comparison graph of both CO_2 and CH_4 is presented inFigure 8.

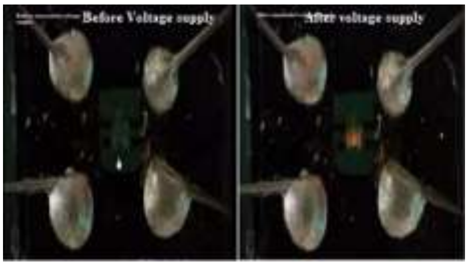


FIGURE9
IMAGESOFTHEPROPOSEDLABYRINTHMICROHEATERSTRUCTUREWITH ANDWITHOUTAPPLICATIONOFSINUSOIDALVOLTAGE.

Table 5 will provide a summary of the findings. We may deduce that the power consumption of the microheater to reach themaximum temperature for $CH_4$is higher than for CO_2. The power is calculated by multiplying the supply voltage and constantcurrentofthe sensimermachine.
Theproposedlabyrinthmicroheaterstructureisexplainedusingasensimerdevice.Themicroheaterproducespulsatingo utput when fed a sinusoidal voltage, and when the temperature is elevated to a very high level, the microheater appears red hot.Thevoltage supplyto themicroheater before andafter itwasapplied isshowninFigure9.

TABLE5
CHARACTERISTICSOFLABYRINTHMICROHEATER

Sl.No.	Material	Voltage Applied	RaiseTime	FallTime	PowerConsumed	AverageTemperature Achieved
1.	CO_2	3.5mV	10ms	6ms	2.8mW	390°C
2.	CH_4	4.5mV	5ms	6ms	3.6mW	410°C

III. CONCLUSION

The design and thermal analysis of a platinum-based new Labyrinth microheater for CO_2 and CH_4greenhouse gases were thesubjects of this study. We used the CleWin 4.1 design tool to design the proposed microheater geometry and a unique sensimerdevice is used for thermal analysis. The experimental results show that the proposed Labyrinth microheater structure can achievethe highest temperature with the least amount of power than other traditional microheater structures. We found that a proposedmicroheater used to break CO_2 atoms had an average temperature of 390°C, whereas a microheater used to break CH_4atoms hadan average temperature of 419°C. We may infer that when we vary the heater temperature from 30°C to 400°C the powerconsumptionandaveragepulsingtimeconstant forCO_2 andCH_4gasesare2.8mWand6msand3.6mWand5ms, respectively.

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