ARPN Journal of Engineering and Applied Sciences

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DESIGN, SIMULATION AND ANALYSIS OF PLATINUM MICRO HEATERS ON AL_2O_3 SUBSTRATE FOR SENSOR APPLICATIONS

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ABSTRACT

This paper presents the design, simulation and analysis of Platinum micro-heaters for sensor applications. Finite element method (FEM) analysis was used to investigate the thermal properties of individual electrically driven platinum micro-heaters. The uniform heat distribution and optimization of power consumption for the micro-heaters were performed by simulating on possible different patterns using COMSOL. Four different patterns of micro-heaters were used in simulation and they are (a) rectangular spiral, (b) diagonal slanting, (c) double spiral and (d) complementary double spiral type. These micro-heaters are designed to ensure minimum power consumption, low thermal mass and better temperature uniformity. The Simulated temperature profile shows that the temperature distribution is uniform over the sensing area. For all the four patterns the temperature profile and power consumption when operated over a supply voltage of 0.5 V to 4 V to obtain an operating temperature from 300 K to 1200 K is compared and presented.

Keywords: platinum micro-heaters, gas sensor, thick film planer heaters, Al_2O_3.

1. INTRODUCTION

The applications of micro-heater devices are expanding rapidly particularly as key components of solid electrolyte based electro-chemical gas sensors for detection of individual gas concentration present in the gas mixtures [1-4] and chemical sensing micro-systems where hotplates are combined with sensitive sensing elements [5]. The micro heaters can also be integrated with humidity sensors to provide an elevated working temperature to the sensors which can avoid the humidity sensor to generate the signal drift [6] and also to reduce the hysterisis of the humidity sensor less than 2% RH [7]. For the separation of reactions in the gas mixture we need to sweep the voltage as well as temperature, for the reduction of water, cathodic polarizations larger than 1V are necessary at T=900K [8]. Alumina is the most cost effective and widely used material in the family of ceramics. As it is having good thermal properties, it can be used as high temperature electrical insulators in order to achieve uniform heat distribution over the geometry [9], In addition to low power consumption, a uniform temperature distribution is required in the active area to ensure equal sensing properties of the whole surface [10-11]. Yttrium-stabilized zirconia (YSZ) is a zirconium-oxide based ceramic, in which the particular crystal structure of zirconium oxide is made stable at room temperature by an addition of yttrium oxide. It becomes an ionic conductor at elevated temperatures, so it can be used as an electro ceramics due to its ion-conducting properties [12]. In order to have good sensitivity and selectivity for the individual components present in the gas mixture it is desirable to use ionic conductors like YSZ as a solid electrolyte [13]. In this paper, we propose a novel design of a uniform high-temperature heater [Pt] using Al_2O_3 substrate for low power multi-gas detection applications.

2. JOULE HEATING AND ELECTRO-THERMAL MATHEMATICAL MODELING OF MICRO-HEATER

The Joule Heating Model node in COMSOL uses the following version of the heat Equation (1) as the mathematical model for heat transfer in solids:

$$\rho C_p \frac{\partial T}{\partial t} - \Delta.\left(k.\Delta T\right) = Q \qquad (1)$$

with the following material properties:
ρ = density
C_p = heat capacity
k = thermal conductivity. (a scalar or a tensor if the thermal conductivity is anisotropic).
Q = heat source (or sink)

In Joule heating, the temperature increases due to the resistive heating from the electric current. The electric potential V is the solution variable in the Conductive Media DC application mode. The generated resistive heat Q is proportional to the square of the magnitude of the electric current density J as per Equation (2). Current density which in turn, is proportional to the electric field, which equals the negative of the gradient of the potential V, so we have,

$$Q \alpha \left| J^2 \right| \qquad (2)$$

The coefficient of proportionality is the electric resistivity $\rho = 1/\sigma$, which is also the reciprocal of the temperature-dependent electric conductivity $\sigma = \sigma$ (T). Combining these facts gives the fully coupled relation in Equation (3).

VOL. 9, NO. 11, NOVEMBER 2014 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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$$Q = \frac{1}{\sigma}\left|J^2\right| = \frac{1}{\sigma}\left|\sigma E\right|^2 = \sigma\left|\Delta V\right|^2 \tag{3}$$

According to Equation (4), over a range of temperatures the electric conductivity σ is a function of temperature T,

$$\sigma = \frac{\sigma_0}{1+\alpha\left(T-T_0\right)} \tag{4}$$

Where σ_0 is the conductivity at the reference temperature T_0, α is the temperature coefficient of resistivity, which describes how the resistivity varies with temperature. Also the power consumption is described in Equation (5) as:

$$P = \frac{V^2}{R} \tag{5}$$

Where V is voltage and R stands for resistance of heating electrode. Here power consumption is directly proportional to the applied voltage and inversely proportional to the resistance of the material. The equations have been solved under Dirichlet, Neumann, and mixed boundary conditions numerically using the Finite Element Method (FEM) when the Electro-Thermal module is selected in COMSOL4.0a. Fixed temperature and potentials are assumed at the endsof the heater. Several material properties are required to solve the mathematical equations mentioned above. In Table-1 and Table-2 the material properties of Platinum and Alumina are shown, respectively.

Table-1. Material properties of Platinum.

S. No.	Parameter	Value
1	Heat capacity at constant pressure (C_p)	133 [J/(Kg*K)]
2	Young's modulus (E)	168e9 [Pa]
3	Thermal expansion co-efficient (α)	8.80e-6[1/K]
4	Thermal conductivity (k)	71.6 [W/(m*K)]
5	Poisson's ratio (μ)	0.38
6	Density (ρ)	21450 [Kg/m^3]
7	Electrical conductivity (σ)	8.9e6 [S/m]

Table-2. Material properties of Alumina.

S. No.	Parameter	Value
1	Heat capacity at constant pressure (C_p)	900[J/(Kg*K)]
2	Young's modulus (E)	300e9[Pa]
3	Thermal expansion co-efficient (α)	8e-6[1/K]
4	Thermal conductivity (k)	27[W/(m*K)]
5	Poisson's ratio (μ)	0.222
6	Density (ρ)	3900[Kg/m^3]

3. EXPERIMENTATION

3.1. Rectangular spiral model

Figure-1 represents the model of Heater Pattern-I.

Materials Used
1. Platinum (Heater)
2. Alumina (Substrate)

Dimensions
1. Platinum-30micron thickness and 100micron Line width.
2. Alumina-(5000 x 5000x 250) microns.

Resistance of Pt : 3.93Ω
Mesh : Tetrahedral
Heat Flux : 5 W/(m^2*K)
Initial Temp : 303K
External Temp : 303K

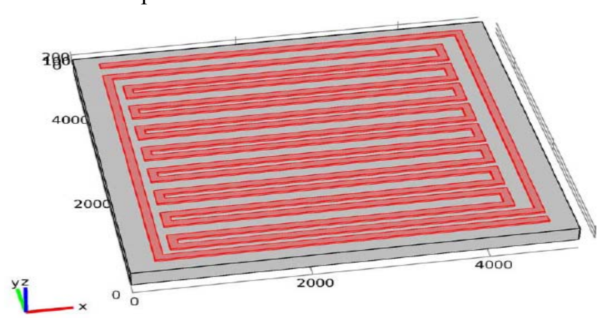

Figure-1. Heater pattern-I.

3.2. Diagonal slanting model

Figure-2 represents the model of Heater Pattern-II.

Materials Used
1. Platinum (Heater)
2. Alumina (Substrate)

Dimensions
1. Platinum – 30 micron thickness and 100 micron line width.
2. Alumina - (5000 x 5000x 250) microns.

Resistance of Pt : 2.7476Ω (It is calculated based on the geometrical values (L, B and T) of platinum line on the substrate model and with the resistivity (ρ) of platinum from material properties (Table-1).

Mesh	: Tetrahedral
Heat Flux	: 5 W/(m^2*K)
Initial Temp	: 303K
External Temp	: 303K

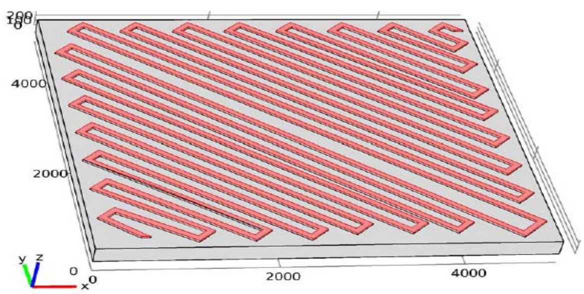

Figure-2. Heater pattern-II.

3.3. Double spiral model

Figure-3 represents the model of Heater Pattern-III.

Materials Used

1. Platinum (Heater)
2. Alumina (Substrate)

Dimensions

1. Platinum - 30micron thickness and 100 microns line width.
2. Alumina - (5000 x 5000x 250) microns.

Resistance of Pt	: 2.6439Ω
Mesh	: Tetrahedral
Heat Flux	: 5 W/(m^2*K)
Initial Temp	: 303K
External Temp	: 303K

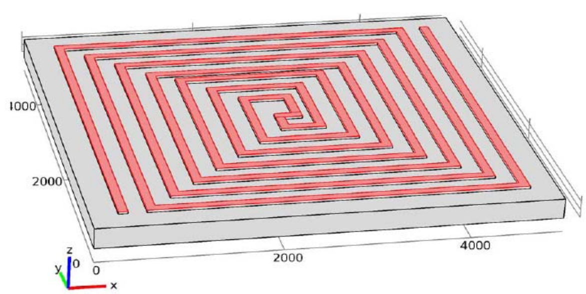

Figure-3. Heater Pattern-III.

3.4. Complementary double spiral model

Figure-4 represents the model of Heater Pattern-IV.

Materials Used

1. Platinum (Heater)
2. Alumina (Substrate)

Dimensions

1. Platinum - 30micron thickness and 100 microns line width
2. Alumina - (5000 x 5000x 250) microns.

Resistance of Pt	: 4.117Ω
Mesh	: Tetrahedral
Heat Flux	: 5 W/(m^2*K)
Initial Temp	: 303K
External Temp	: 303K

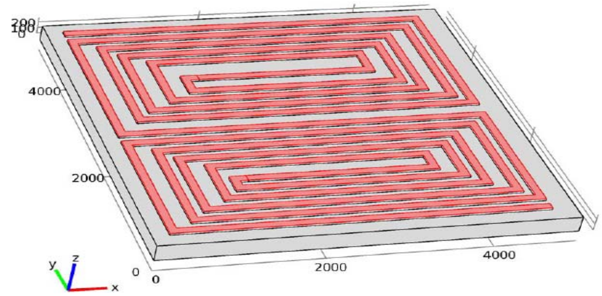

Figure-4. Heater pattern-IV.

4. RESULTS

4.1. Heater pattern-I

The Figure-5 represents the simulated result Heater Pattern-I for 4Volts input.

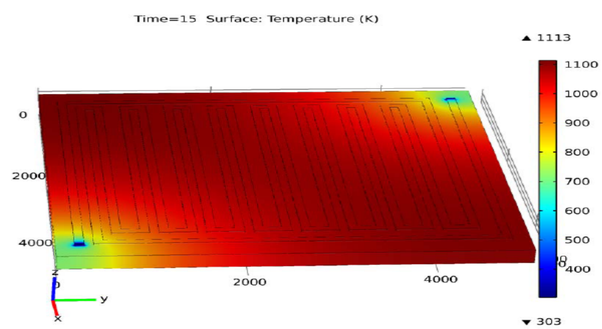

Figure-5. Simulated Result.

The Figure-6 represents the time response for Heater Pattern.

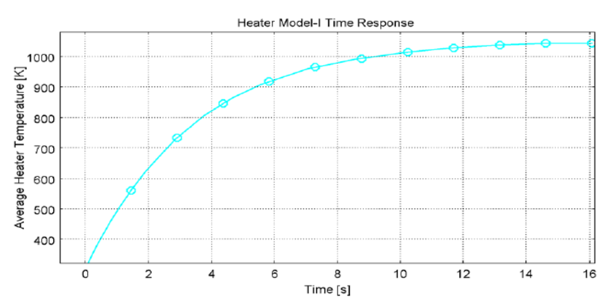

Figure-6. Time response.

VOL. 9, NO. 11, NOVEMBER 2014 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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4.2. Heater pattern-II

Figure-7 represents the simulated result of Heater Pattern-II for 4 Volts input.

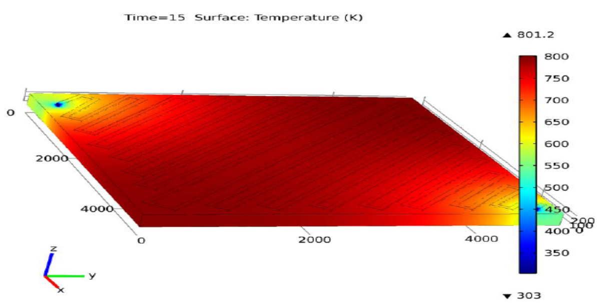

Figure-7. Simulated result.

The Figure-8 represents the time response for Heater Pattern-II.

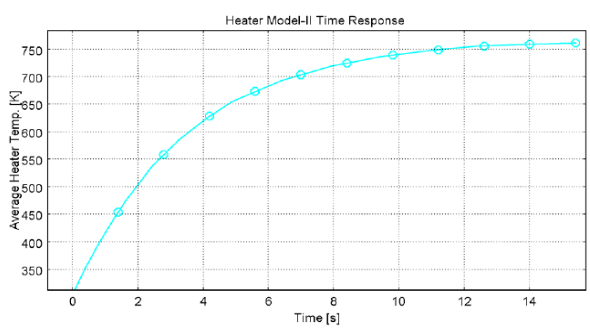

Figure-8. Time Response.

4.3. Heater pattern-III

Figure-9 represents the simulated result of Heater Pattern-III for 4Volts input.

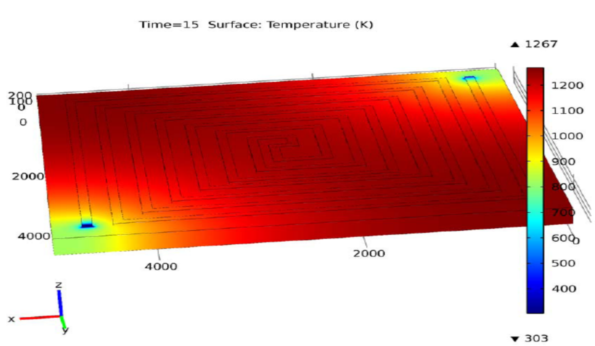

Figure-9. Simulated Result.

The Figure-10 represents the time response for Heater Pattern-III.

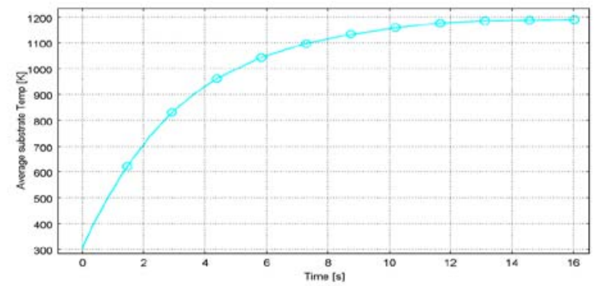

Figure-10. Time response.

4.4. Heater pattern-IV

Figure-11 represents the simulated result of Heater Pattern-IV for 4Volts input.

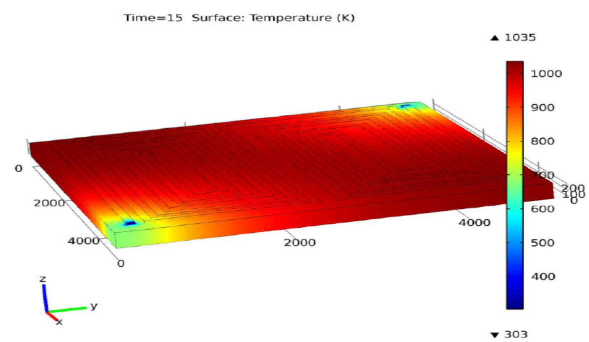

Figure-11. Simulated result.

The Figure-12 represents the time response for Heater Pattern-IV.

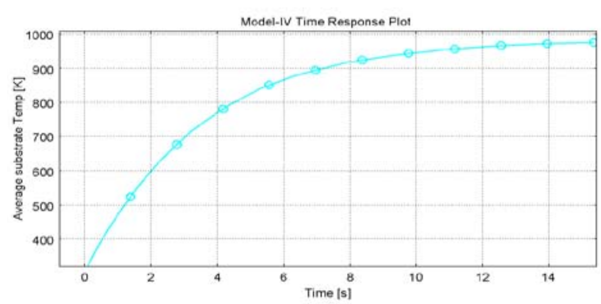

Figure-12. Time response.

5. DISCUSSIONS

Figure-13 represents the comparison graph of input electrical power with the average substrate temperature for all the four different types of heater patterns. Figure-14 indicates the comparison of time response of all four different patterns. As Alumina is having excellent thermal properties, a very uniform heat distribution throughout the substrate is achieved in all the four different heater models. When it is compared with other kind of materials like SiO_2 etc., instead of alumina as the substrate, uniform heat distribution is not obtained rather it is giving less average temperature for the same amount of input power, as well as red hot at the middle of heater which is not deserved. When alumina is used with platinum combination for developing the heater, it is giving excellent temperature even for small amount of input electrical power. As a trial, four different heater models with Pt, Al_2O_3 combination has been made and analyzed. Based on the analysis from Tables (4-7) it is observed that, the pattern-I (Rectangular Spiral Model) is exhibiting good characteristics compared to the pattern II, pattern III and pattern IV and also based on the observation from the Table-8, the response time of pattern -I for an applied voltage of 4Volts is very close to the other patterns under same operating conditions and the response is very promising.

6. CONCLUSIONS

i. Uniform Heat Distribution could be obtained throughout the substrate by means of identifying a critical heater pattern.
ii. Optimization of input electric power consumption for a very wide temperature profile could be able to achieve by using suitable materials and developing a critical heater pattern.
iii. The temperature could be varied from 300K to 1200K with uniform heat distribution and with optimum power consumption and also with promising time response by means of effective designing and material selection.

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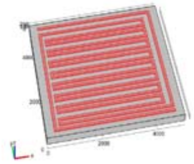
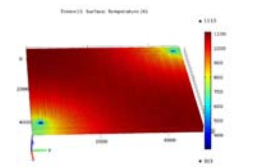
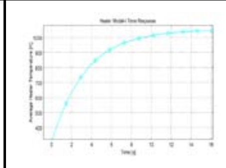
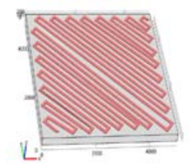
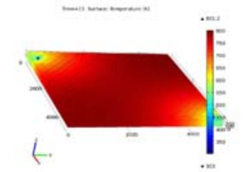
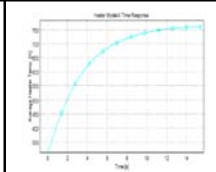
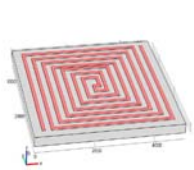
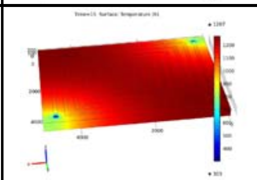
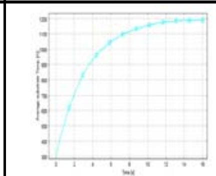
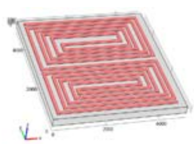
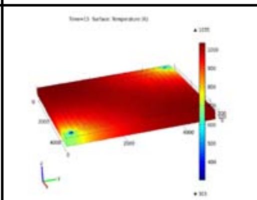
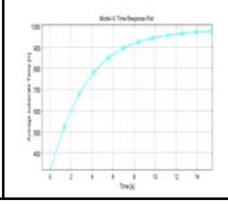
9. APPENDIX

Table-3. Performance Comparison table.

Pattern No. and Name	Pattern picture	Simulation results	Response time	Temperature uniformity (% variation)	Observations and comments
Pattern-I (Rectangular Spiral Model)				Max.Temp: 1113K Average Temp: 1044k Temp Variation:6.6%	1. Uniform Temp. Distribution 2. Faster Response 3. Less Power Consumption
Pattern-II (Diagonal Slanting Model)				Max.Temp: 801.20K Average Temp: 761.557k Temp Variation:5.2%	1. More Uniform Temp. Distribution 2. Faster Response 3. More Power Consumption
Pattern-III (Double Spiral Model)				Max.Temp: 1267K Average Temp: 1189.94k Temp Variation:6.5%	1. Uniform Temp. Distribution 2. Faster Response 3. More Power Consumption
Pattern-IV (Complementary Double Spiral Model)				Max.Temp: 1035K Average Temp: 976.08k Temp Variation:6.0%	1. More Uniform Temp. Distribution 2. Faster Response 3. More Power Consumption

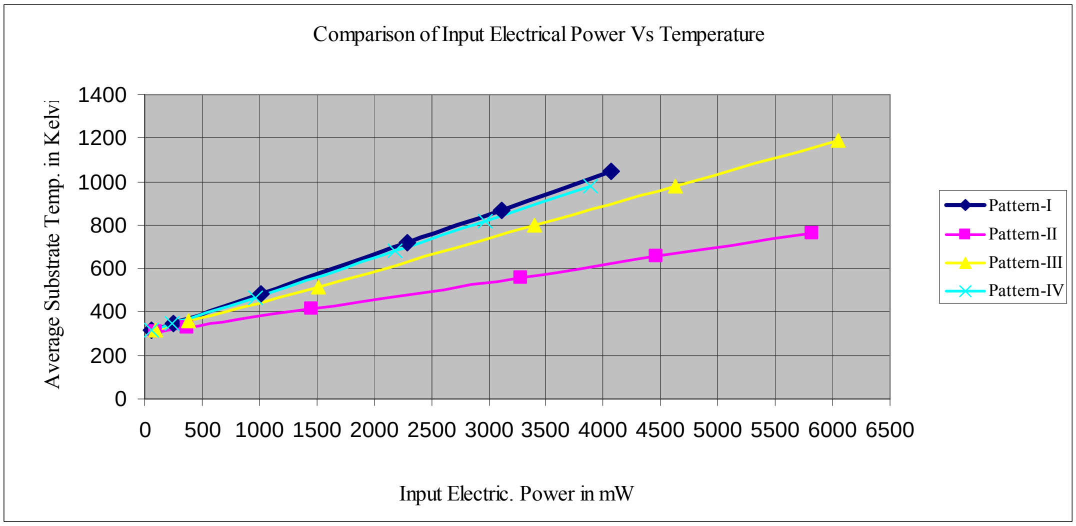


Figure-13. Comparison of input electrical power Vs temperature for all the four types of heater models.

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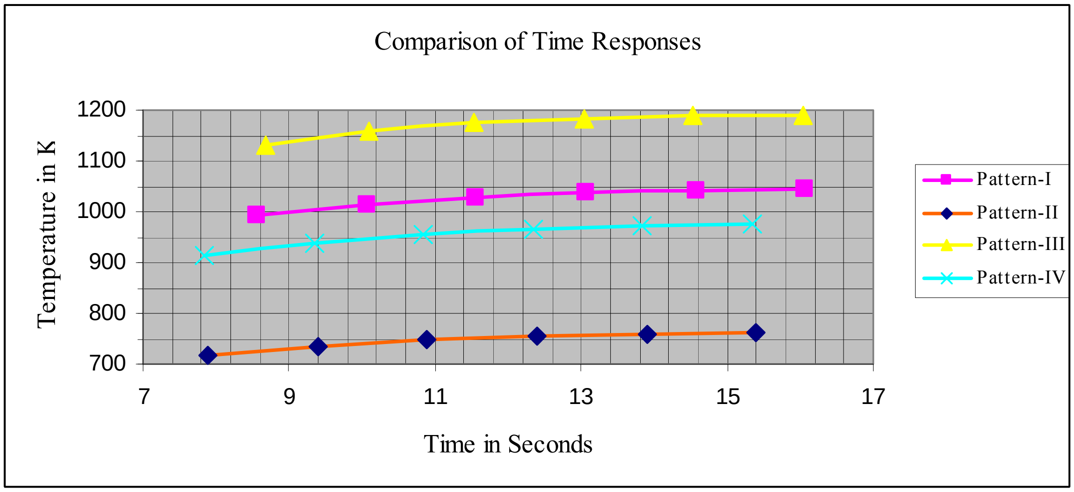

Figure-14. Comparison of time responses.

Table-4. Input power Vs average substrate temp tabular column for heater pattern-I.

S. No.	Applied voltage in (V)	Simulated time in (S)	Elect. Power in (mW)	Average substrate Temp. in (K)
1	0.5	10	63.613	314.087
2	1	10	254.453	347.924
3	2	10	1017.81	481.224
4	3	15	2290.07	719.214
5	3.5	15	3117.04	867.556
6	4	15	4071.24	1044.001

Table-5. Input Power Vs average substrate temp tabular column for heater pattern-II.

S. No.	Applied voltage in (V)	Simulated time in (S)	Elect. power in (mW)	Average substrate Temp. in (K)
1	0.5	10	90.98	309.854
2	1	10	363.95	330.429
3	2	10	1455.81	412.972
4	3	15	3275.58	560.574
5	3.5	15	4458.44	654.549
6	4	15	5823.26	761.556

Table-6. Input power Vs average substrate temp tabular column for heater pattern-III.

S. No.	Applied voltage in (V)	Simulated time in (S)	Elect. power in (mW)	Average substrate Temp. in (K)
1	0.5	10	94.557	316.289
2	1	10	378.229	356.743
3	2	10	1512.92	516.568
4	3	15	3404.06	799.504
5	3.5	15	4633.30	981.578
6	4	15	6051.66	1189.938

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Table-7. Input power Vs average substrate temp tabular column for heater pattern-IV.

S. No.	**Applied voltage in** (V)	**Simulated time in** (S)	**Elect. power in** (mW)	**Average substrate Temp. in** (K)
1	0.5	10	60.72	313.07
2	1	10	242.89	343.82
3	2	10	971.58	463.80
4	3	15	2186.05	680.839
5	3.5	15	2975.46	817.585
6	4	15	3886.32	976.079

Table-8. Comparison of time response under steady state condition.

S. No.	**Pattern-I**		**Pattern-II**		**Pattern-III**		**Pattern-IV**	
	Time (S)	**Temp** (K)	**Time** (S)	**Temp** (K)	**Time** (S)	**Temp** (K)	**Time** (S)	**Temp** (K)
1	8.5663	991.402	7.8967	718.5287	8.6718	1132.311	7.8398	915.4717
2	10.0663	1012.2677	9.3967	735.9441	10.1022	1157.818	9.3398	938.7319
3	11.5663	1027.5928	10.8967	747.785	11.5326	1175.008	10.8398	953.955
4	13.0663	1037.858	12.3967	755.1839	13.0326	1184.263	12.3398	964.9106
5	14.5663	1042.9728	13.8967	759.2982	14.5326	1188.294	13.8398	972.0526
6	16.0663	1044.001	15.3967	761.5557	16.0326	1189.938	15.3398	976.0786