Design of MEMS Based Mini-Catamaran

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Abstract

A design is presented for a Micro-ELectro-Mechanical-System(MEMS) based Mini-Catamaran, which works on the concept of Machian Propulsion. The MEMS based boat works utilizing steam as the power source s giving it high stability and high speed. The Mini-Catamaran is designed with the Micro-Boiler using MEMS heater situated on each boat on either side of the platform. The movement and the steering operation of the boat is achieved by differential heating of the dual Micro-Boiler. The operation of the boat is controlled through a GPS based command system. Instead of using fuel or gas, the boat works with the use of steam formed by the Micro-Boiler which is powered by renewable energy source.

Keywords— MEMS, Micro-Boiler, Catamaran, Micro-heater

I. Introduction

In the present technological era, the need for miniaturization of devices has become the prime factor for establishing various state-of-art technologies. Several types of miniature machines have been fabricated earlier, although there has been a particular inclination in the areas of micro-sensors and microactuators.[1]-[4] This miniaturization of devices has been gradually taken place in the area of Naval and Defence technologies[5],[6]. Similar to boats used in navy for defence purposes, the need for mini-boats have become a target of interest for spying and environmental monitoring purposes[7]. There have been a number of attempts to miniaturize actuators and sensors related to water, attracting increased interest with the investigation of new floating methods and propulsion mechanisms for environmental applications such as water quality monitoring etc.

In recent years, many studies have been conducted on various kinds of microrobots which are able to move on water [8]-[16] and have been reported by several research groups. The previous studies mostly focused on water strider robots[8]-[10], and studies on other propulsion mechanisms were also conducted[11]-[15]. But, these researches had major drawbacks such as a large volume, low speed, and short lifetime. The development of stable device was needed which would further increase the scope for industrial as well as defence applications.

In this paper, we describe our MEMS based micro-boiler which is incorporated in a Mini-Catamaran boat with the engines as the Micro-Boiler and an electronic control system to control the boat. This Catamaran boat can be used for defence applications which show high perseverance with relatively high speed due to its two engines. Catamaran has a greater advantage over traditional single or monohull boats as it comprises of two boats connected by a platform. This serves as an important factor giving it higher stability, speed compared to others[19]. Using this structure, modifications has been made in this paper using MEMS based Micro-boiler as the engine which along with propulsion[20] also helps the boat to steer in any direction as per required. The steering can be done by tuning the voltage supply to differentially heat the Micro-Boilers. The added allure of renewable energy source- light energy, shows the novelty and usefulness of the design and concept.

This is the first approach using Catamaran as a boat and using Micro-Boilers for movement and steering purposes. The proposed model can be a subjected to different modifications when it comes to the electronic system which controls the operation of the boat. This model can have a large application in industry as well as defence domains.

II. Innovation in Design

The Micro-Boiler is designed based on the use of steam as the propulsion mechanism for the Catamaran boat. This steam propulsion theory is known as Machian Propulsion. Though several attempts to miniaturize boat propulsion mechanism[11]-[15] have been made earlier, our approach has capability to be the most stable and high speed micro-actuator used as a propulsion engine.

I. *Design*

In Fig 1. the proposed structure of the MEMS based actuator is shown which works as the engine for the Catamaran. It consists of separately fabricated top and bottom silicon substrates that are bonded in the final stage of fabrication. The water cavity is prepared by bonding the two substrates.The bottom substrate consists of the cavity with two propulsion nozzles. On the top substrate, micro-heater is fabricated which helps to heat up the water in boiler cavity which in turn is converted to steam for the propulsion of the boat.

The Micro-Boiler shown in Fig.1 is not only responsible for the propulsion of the catamaran, but it also controls the steering of the boat in the desired direction. It will be seen in section III, that the speed of ejection of the water from the propulsion nozzles is much greater than that of the inflow, thus helping the boat to move forward. Taking in account of the thermodynamics of the system, it can be seen that as the temperature of the heater increases, more faster is the change of water into steam thus faster speed is attained. Thus, there is a direct relation between the temperature of the heater to the speed of the boat. Exploiting this phenomenon, we can achieve the control to steer the boat in preferred direction by increasing the current delivered to the heater, increasing temperature thus increasing speed. The dual Micro-boiler thus can be subjected to differential heating which in turn helps the boat to steer.

Thus, we can see dual Micro-Boiler incorporated in the boats will not only give the Catamaran much higher speed, but also give us the availability to steer the boat just by changing the input current. Now, the reason for using Catamaran rather than any other boats is described clearly in section IV.

II. *Architecture and Dimensional Details*

The heater is the integral part for the Micro-Boiler which serves as the engine of the Catamaran. It was seen that for micro-heaters the geometry played a major effect on its distribution of temperature.[22]. There can be several types of design which can be incorporated for the fabrication of the Micro-heater which are chosen as per requirement.

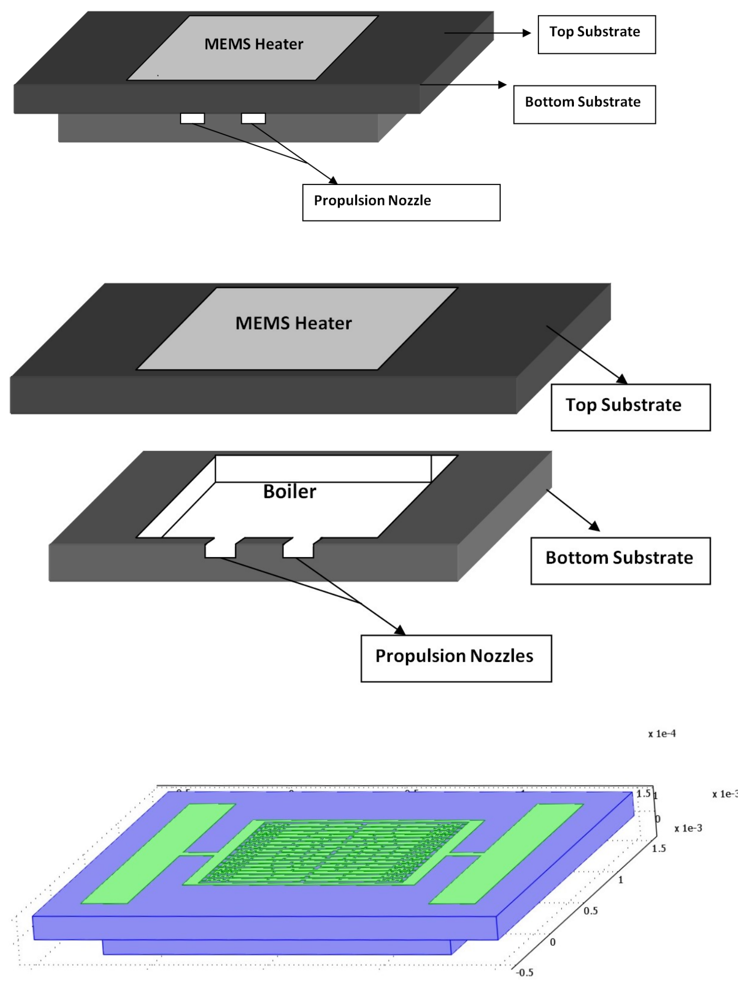


Figure 1: *Structure of the proposed Micro-Boiler for the Mini-Catamaran.*

The micro heater that is used in this paper has a combination of parallel and meandering geometries, which is seen to have the most uniform temperature distribution and which serves good for our requirement for the engine. In section V, it is shown how the temperature distribution changes as the heater geometry is changed, thus getting the most uniform distribution of temperature. The micro-heater designed is capable to produce highest temperature, capable of boiling the water in the cavity.

The dimension of the micro-heater which is used will have a overall length and width of $1mm$ in Fig 2. The height of the heating element made of aluminum will be of $1\mu m$. Aluminum is used as heating element due to its high melting point ($\sim$ 660.3 °C), high resistance to corrosion. It has a high electrical conductivity, has a stable temperature coefficient of resistance, and also good chemical and thermal durability. Micro-heater using aluminium serves as to be more robust when the devices operate at relatively high temperature.

After fabrication of the heater the boiler part comes into the picture. The bottom substrate consisting of the boiler is smaller than the size of the substrate used for the heater. The etched out cavity formed to serve as the boiler for water intake will be of the same size of the cavity in the heater.

The whole device has an overall length of $2mm$ x $2mm$, with the heater on the top of the substrate. The bottom substrate has an overall length of $1.5mm$ x $1.5mm$. The cavity inside the bottom substrate has a depth of $200\mu m$ and a size of $1.1mm$ x $1.1mm$. The upper substrate with a slightly larger area acts as a cap for the bottom substrate, to prevent leakage of water from the boiler.

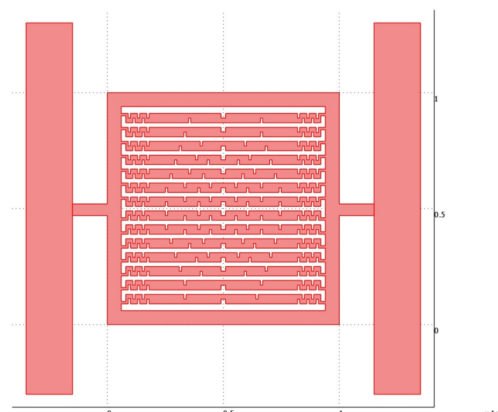
III. Principle of Operation

We have used the theory of Machian propulsion[20] which is based on propulsion by generation of steam. As the water keeps coming into the cavity, the heater turned on. When heat is applied to the boiler, water in the boiler evaporates, producing steam. The expanding steam is suddenly pushed out of the boiler and pushes some of the water out the cavity through the propulsion nozzles, propelling it forward.The boiler or the cavity being dry, cannot, therefore, generate any more steam. The momentum of the column of water in the exhaust tube keeps it moving outward, so that the pressure inside the boiler drops down below the atmospheric pressure.

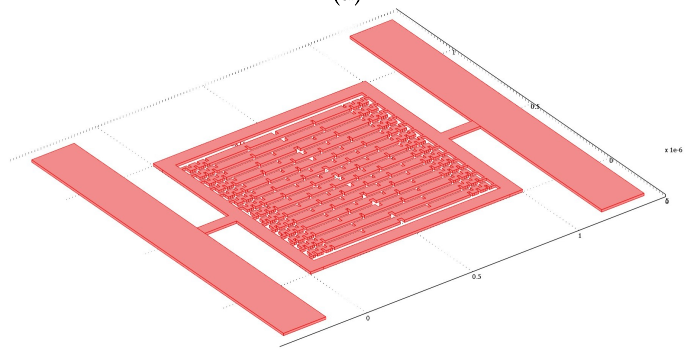
The pressure outside the boiler now forces water back into the boiler. This water then boils and the cycle of alternate suction and ejection repeats. The water expelled from both tubes during the first phase of the cycle, and drawn in from both tubes during the second phase of the cycle.

Thus as discussed above, Catamaran is propelled forward by the alternate suction and ejection of the fluid across its pipes' orifice, thus having the net mass flux being zero. Yet, there is a net forward thrust developed because, during the outflow, the flow is an axi-symmetric jet confined to a narrow domain and does not diverge much for reasonable distances.

The flow during suction can be thought of as similar to the flow induced by a sink flows through pipes simultaneously. The inflow is of the same magnitude but it does not produce an equal and opposite thrust and is much smaller compared to the thrust produced during ejection as shown in Fig.3.



(a)



(b)

Figure 2: *Structure of the parallel and meandering MEMS heater*

The inflow is of the same magnitude but it does not produce an equal and opposite thrust and is much smaller compared to the thrust produced during ejection as shown in Fig.3. The difference between how the inflow and outflow is critical in the study of fluid mechanics. It can be easily seen that we cannot 'suck out' a candle but we can easily 'blowout' a candle even though the average velocity near the lips is nearly the same for both of the situations. The asymmetry of the shapes of the inflow and the outflow is a consequence of the viscosity of water, whereas the catamaran would be able to operate in an ideal fluid. Furthermore, as they pass through the orifices,the outflowing and the inflowing water carry the same momentum but in opposite directions, relative to the boat. The important difference is that the momentum of the outflow is expelled, whereas the momentum of the inflow is soon transferred to the boat.

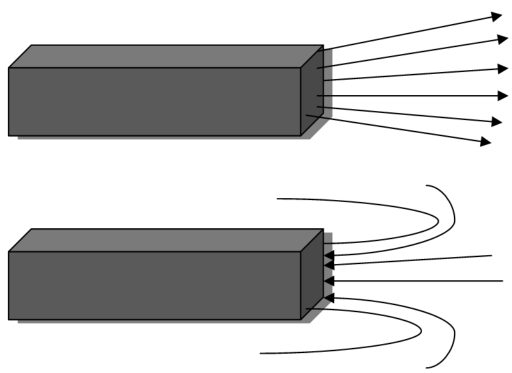


Figure 3: *Outflow and Inflow of water from an orifice*

IV. Design of Catamaran

For the application of this actuator, we propose a design of the catamaran to be used in defence applications for water monitoring as well as spying operations.

I. Why Catamaran?

We know, the catamaran consists of two boats with one adjoining platform. This design of boat has been extensively used for its higher stability. Exploiting it's advantages, a mini version of this catamaran is designed which can run through the dual MEMS engine with Micro-Boiler defined above with slight modifications.

In designing boats of small dimension, packing electronic system with engine inside the boat can become a difficult task to accommodate. This problem is solved by the platform between the boats of the catamaran thus giving ample space for the placement of the engine as well as a electronic system which gives the catamaran a higher advantage over other boats.

Another most important use of the Catamaran is the use of dual Micro-Boiler. This option is only available because of the use of two boats which is connected together. The dual Micro-Boiler is the main attraction of using this boat as it not only serves as a engine but also helps the boat to steer in any preferred direction when required as discussed above. This steering is done by the differential heating of the Micro-Boilers by changing the input voltage. This tuning of voltage can be done in the range of 6V-10V. This versatility of the dual Micro-Boiler proves to have higher advantage and efficacy than any other models.

As seen in Fig.4, our proposed design of the catamaran have two MEMS engines incorporated on each boats. Each boat have two orifices which extend till the opening of the propulsion nozzles of the MEMS engine.

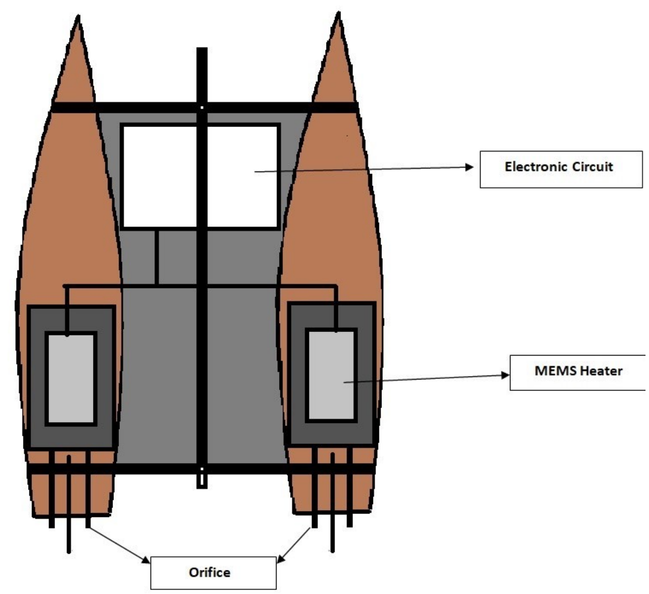


Figure 4: *Design of the proposed Mini-Catamaran*

II. Power Source

Now, identifying a satisfactory method for supplying electrical power to the controllers and actuators is a major step in the design process. For the boat the use of a micro power supply can prove to be advantageous for heating

Table 1: *Material Properties of layers of micro-heater*

Material	Si	SiO_2	Au	Al
Young's Modulus(GPa)	140	74.8	79	69
Density(kg/μm^3)	2.33 e-15	2.27 e-15	1.93 e-14	2.7 e-15
Poisson's Ratio	0.17	0.2	0.415	0.334
Thermal Conductivity(pW/μmK)	150 e+6	1.4 e+6	3.10 e+8	2.05 e+8
Specific Heat(pJ/Kg.K)	7.12 e+14	1.0 e+15	1.3 e+14	9.03 e+14
Dielectric Constant	1.19e+1	3.9	6	1.8
Electrical Conductivity(s/m)	-	-	4.10 e+7	3.53 e+7
Melting Point($^{\circ}C$)	1414	1600	1064	660.3

as well as for the light weight. Like any power supply system, the micro power supply must be composed of three parts-

1. Energy Source
2. Energy Capture
3. Energy Storage and delivery

We know that the most useful and readily accessible energy source is light energy. Light energy can be obtained from sun. Using a photovoltaic cell to capture the energy, light can be harnessed to produce an electrical current. The electrical current produced by the photovoltaic cells can be used to drive the MEMS heater to perform. First, the current can be routed directly to the controllers that would, in turn, route current to heater when needed.

This configuration would be sufficient assuming that lighting conditions were always optimal, but would not allow for any auxiliary power, should light levels drop below the operating threshold.

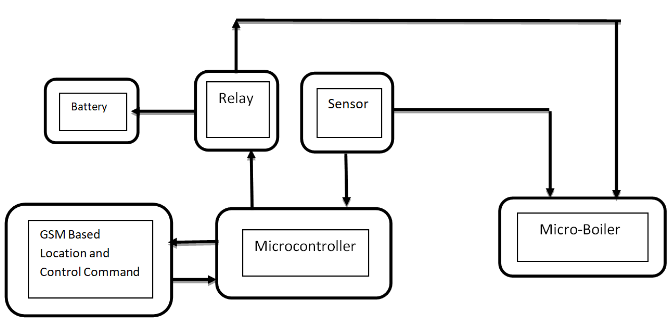


Figure 5: *Block Diagram of the control system to monitor operations on the Mini-Catamaran*

In order to ensure operation in non-optimal lighting, a method of power storage is necessary. The second and more desirable way to configure the photocells is in conjunction with a battery. The photocell would charge the battery, and the battery would drive the engine. Further, the photocell could temporarily be used along with the battery if higher voltages or currents are required.

To control such operations an electronic system is a must which will be placed on the platform of the catamaran. This will be externally controlled using GPS based control command for finding it's location and movement. This signal is captured by microcontroller to control different operations. The battery will be switched on through the microcontroller thus switching on the Micro-Boiler through relay. The temperature of the heater can also be sensed through a sensor which in turn gives microcontroller to control the current to be delivered as and when required for a particular desired temperature. The temperature sensor to be used can be a J-Type thermocouple. After the Catamaran starts moving, it's movement can also be controlled thorough GPS based control system using command given to the microcontroller. The block diagram of the whole process is shown in Figure 5.

V. Theoretical Analysis and Simulation Results

The design of the heater in Fig 2, was proposed to improve the uniformity of the heat dissipation across the heating plate. Since the heat loss of the micro-heater takes place in both the x and y directions, compensation should be considered in both directions. In Fig 2(a), there is no potential difference along the y-direction. Since the voltage is constant, the power consumption is given by-

$$P = \frac{V^2}{R} \tag{1}$$

The power consumption of the heater applied is inversely proportional to resistance. Therefore, a reduction in resistance in the outside area of the micro-heater will lead to an increase in power consumption; subsequently increasing the heating temperature. Therefore, in the y-direction, the outer area is designed to have a coarser and larger pattern of Aluminum than at the center in order to decrease resistance and hence temperature.

Along the x-direction in Fig 2(a), the electrode and the heating plate are connected in series. Therefore, the current flowing along the x-direction is equal. Since the current is constant, from Eq. (2):

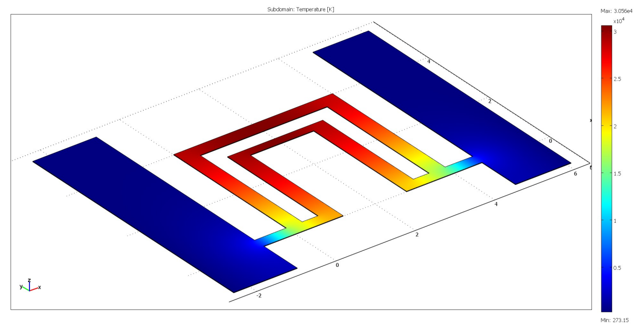
$$P = I^2 R \tag{2}$$

The power consumption is proportional to the resistance. Therefore the heating temperature of the outside area of the micro-heater can be increased by increasing the resistance of the outer area of the heater to compensate for the heat loss in the vicinity of the silicon substrate. Therefore, in the x-direction, the outside area has a smaller and denser pattern of than at the center area in order to increase the resistance and hence temperature.

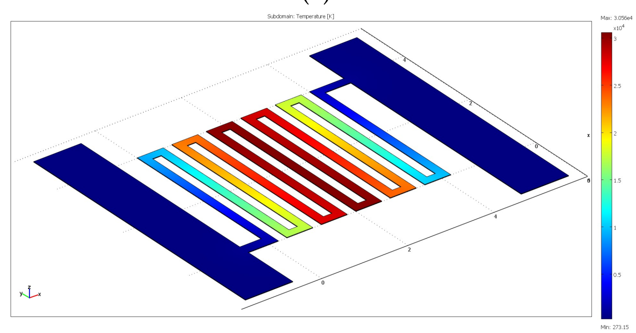
A series of heater structure was designed for the Micro-Boiler to meet its requirement of boiling water inside the cavity which would help in propulsion of the boat. For attaining higher temperature and distribution, a heater with a uniform distribution of temperature was needed.

After simulation, Fig 6(d), served to be the most useful design which attained highest temperature, which is capable of the boiling operation of water in the cavity of the Micro-Boiler. A temperature of more than 1000K was achieved when operated at a voltage of 6V.

The first geometry designed is shown in Fig. 6(a). The heater was designed with a parallel geometry, but it lacked the uniform distribution of temperature. The temperature achieved by the heater was 284 K which did not serve the purpose of the heater. The second geometry was of meandering geometry shown in Fig 6(b). The figure shows non-uniform distribution of temperature and also temperature achieved was quite low. So, a third design of the heater was simulated as shown in Fig 6(c). Here, a uniform distribution of temperature was achieved and which was working at a temperature of 390 K.



(a)



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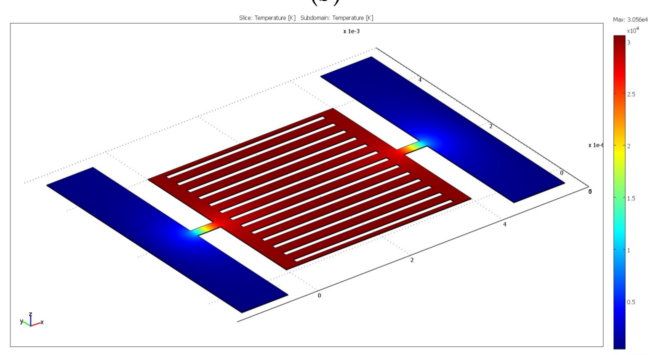

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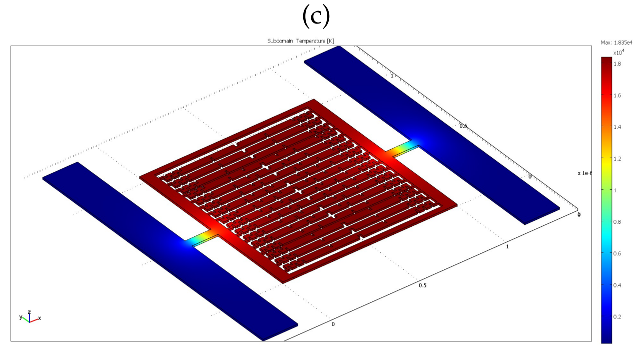
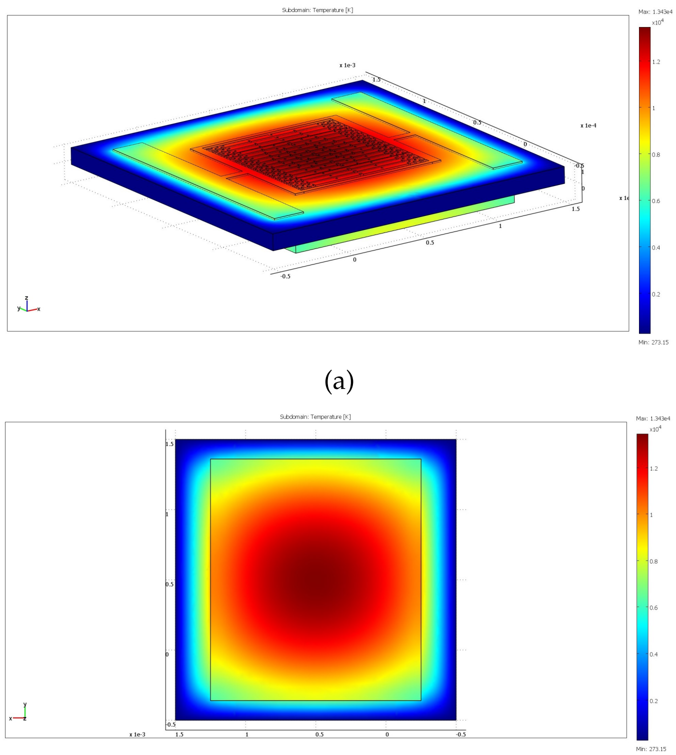


(d)

Figure 6: *Simulation of MEMS Heaters for use in the Micro-Boiler*

Thus, changing this design to have parallel and meandering structure, we obtained the design as shown in Fig

6(d) which had uniform distribution as well as worked at highest temperature, which was sufficient to work as the heater for the Micro-Boiler.



(a)

(b)

Figure 7: *Temperature distribution of the Micro-Boiler (a) Simulation of 3D model of the Micro Boiler (b) Distribution of heat at the bottom substrate*

When the device is to be fabricated, the heat generated for the boiling operation will be much lower than shown in the simulation as the heat losses is not accounted here. Our purpose of propulsion of the boat will be served if the heater after fabrication can generate a temperature of 350K-380K. Our design is capable of producing such temperature which will be feasible to propel the boat.

After the simulation of the MEMS Heater, the Micro Boiler was designed with substrate size of 2mm x 2mm. The bottom substrate which was of size 1.5mm x 1.5mm, with a cavity of 1.1mm x 1.1mm with a depth of 200 μm. In Fig 7(a), it is seen the temperature distribution of the heater on the silicon substrate. The heat is conducted through the substrate to heat up the water inside the cavity. The heat distribution of the bottom substrate is shown in Fig 7(b). Temperature rise to its' maximum at the middle of the substrate with the high heating region confined in area of approximately 1mm x 1mm. This helps the heat to be maximum for the area of the cavity, thus helping in faster heating of water.

VI. Fabrication Feasibility

I. Fabrication Procedure-

The top substrate is fabricated with the heater and the bottom substrate consists of the cavity with two nozzles. The boiler and the heater are to be fabricated separately and then placed together. When both substrates are completely processed, they will bonded using epoxy. The top substrate forms as a cap for the bottom substrate which helps to form an enclosed cavity for the boiler.

I.1 Fabrication of MEMS Heater-

The MEMS Heater will be designed on a 2mm x 2mm substrate area of a silicon substrate and a thickness of 400μm with device layer of 30μm. Using photolithography, the heater is fabricated. First, a 4μm -thick silicon oxide (SiO_2) layer is grown onto the substrate by thermal oxidation and is etched to give it a shape as the micro-hotplate. The use of the SiO_2 layer is to insulate substrate and the heating element. After that a 1μm aluminium layer which is the heating element is deposited onto the SiO_2 layer using the sputtering method. This aluminium layer is patterned to form micro-heater shapes. It is then etched out by dry etching to form parallel and meandering geometry for attaining uniform temperature distribution. After that the capping is done by anodic bonding using glass with a glass cavity depth of 5μm. A deposition of 0.5μm of gold on either side of the heater is done to form the two electrode pads.

I.2 Fabrication of the boiler with propulsion nozzles-

The bottom substrate consists of two propulsion nozzle and a deep cavity and is fabricated using photolithography. Firstly, silicon oxide is grown by thermal oxidation on the 400μm thick silicon substrate. Then, it is patterned on the front of the bottom substrate to give the shape of the cavity with the two propulsion nozzles. After that, the layer is etched out to give shape to the cavity and the two propulsion nozzles. The cavity formed is of length 1.1mm

x 1.1mm and is of 200μm in depth, with two propulsion nozzles of the same depth.

VII. Conclusion

This paper has proposed a design for a catamaran using Micro-Boiler working with the use of Machian Propulsion theory. The Micro-Boiler uses a heater with a cavity in the middle and two propulsion nozzles. The two Micro-Boilers are situated on each boat of the catamaran. The main novelty of the concept is the steering operation of the boat which is controlled by differential heating of the dual Micro-Boiler. This MEMS based Micro-Boiler is powered by a battery, which stores light energy. To control the operation of the boat, an electronic control system based on GPS technology is used. The Catamaran proposed can have various application for defence and spying and can sustain in water due to it's high stability, speed and also due to use of renewable energy.

VIII. About the author

Shirshendu Chatterjee is a 4^{th} year B.Tech student at the Institute of Radiophysics and Electronics, University of Calcutta.

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