MEMS based Active Cooling System

Project report submitted in partial fulfilment of the degree of Electronics and Communication Engineering

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1 MEMS based Active Cooling System

Abstract

As computing devices become more powerful, efficient thermal management solutions are crucial. Modern processors generate significant heat, necessitating advanced cooling systems that meet current standards. However, existing cooling methods often fall short in terms of space, noise, and power consumption. In our report, we propose a MEMS-based cooling device for computing systems. MEMS technology offers compact size, low power usage, and minimal noise. Our design is based on the principle of jet impingement. We also discussed the fabrication process of this innovative cooling solution.

Keywords: thermal, airflow, MEMS, cooling, membrane

2 Introduction

As advancements in semiconductor technologies reach new heights, modern computing devices enjoy higher speed and more computing power. This is essentially due to feature sizes getting smaller, and efficient packing of transistors into smaller and smaller spaces. However, ever-increasing processing capabilities accompany the challenges raised due to heating issues, which limits the devices from realizing their full processing potential.

Many devices nowadays perform what is known as throttling in order to balance out the excessive heat. In this process, whenever the device reaches a certain threshold of temperature, the processor’s clock speed is reduced, indirectly affecting its performance. Heat, thus, is one of the biggest bottlenecks in computing, and thermal management has become an increasingly important issue. Moreover, the active cooling systems currently employed in modern computing devices have yet to keep pace with the advancements in processor technologies and thus fail to solve the ever-growing heating issues. Current active cooling solutions primarily involve the usage of electric fans that have rotating blades and blow air onto the internal components to cool them down. Such systems not only have the inability to cool the device efficiently but also pose problems in terms of space, noise, and power consumption.

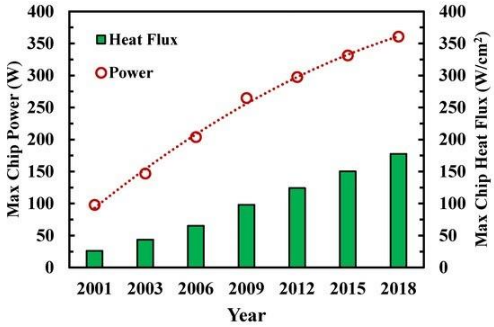


Fig. 1 Relation between heat generation and chip power consumption

Therefore, we have designed a MEMS-based system that will aim to solve the problems in all of the mentioned areas simultaneously.

3 MEMS based fan

It consists of a MEMS-based membrane with a piezoelectric layer on top of a substrate for creating a particular vibrational motion. Piezoelectric materials are materials that, when provided with electric voltage, create a mechanical motion by expanding and contracting.[1] Thus, the piezoelectric layer is a key component of the membrane, responsible for converting electrical energy into mechanical vibrations.

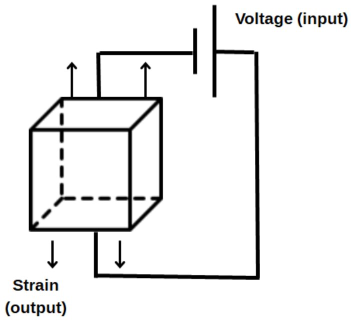
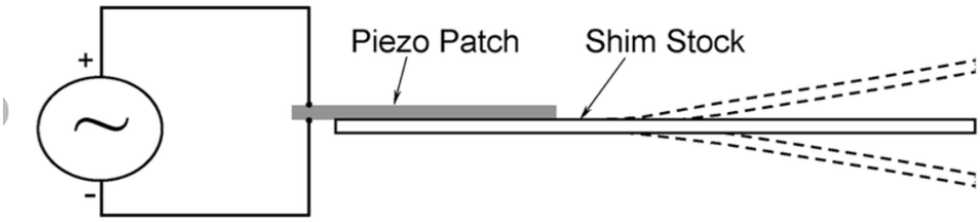
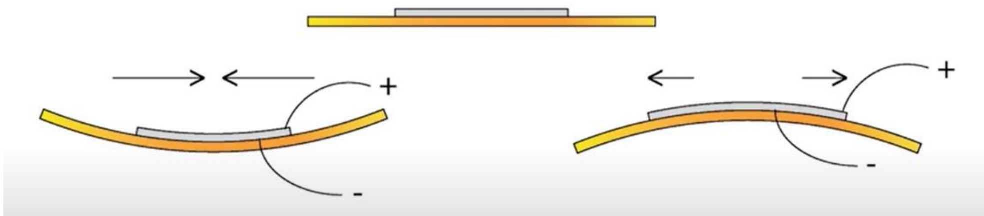


Figure: Piezoelectric Effect

The membrane vibrates in a specific fashion to generate high-velocity pulsating jets of air for efficient cooling.



Schematic of a piezoelectric fan oscillating under an applied voltage due to the contraction and expansion of a piezoceramic patch.



4 Working Principle

The central operating principle of this device relies on jet impingement, a cooling technique commonly employed in jet airplane engines. In this method, high-velocity fluid jets are directed onto the surface of the target component for efficient cooling. The fluid used can be either a liquid (such as water or coolant) or a gas (such as air). For our specific application of active cooling in computing devices, we will utilize air as the cooling medium.

The high-velocity fluid first impacts the surface perpendicularly (refer Fig. 2) and creates a thin film of fluid that spreads out radially. Heat is then transferred from the surface to the fluid through convection. The high velocity of the fluid is particularly important as it increases the heat transfer coefficient and also helps to break the boundary layer of heat on the hot surface, thus allowing maximum heat transfer from the surface to the fluid and removing the heat from the surface rapidly. Therefore, for the same volume of air, the higher the speed, the more heat it can remove [2].

The device will consist of a MEMS-based cooling element that will vibrate in a particular fashion, pull the air down from the top vents, and will direct that air downwards as pulsating jets. The vibration of the cooling membrane will happen with a frequency that creates a huge backpressure. This backpressure is required for the air to overcome the resistance due to limited space inside the device and to make it flow at high velocity.

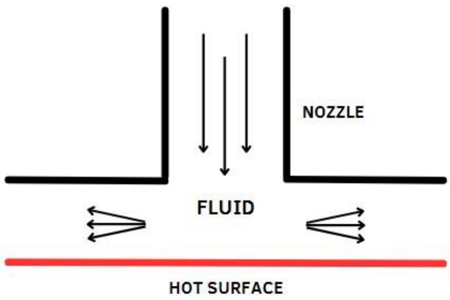


Fig. 2 Jet Impingement

The air will first enter the top chamber from the top vents, is directed towards the bottom plate, and will enter the bottom chamber through the orifices (refer Fig. 6). The orifices are small nozzles that direct the airflow at high velocity downwards towards the heat spreader. This is where the principle of jet impingement operates. The high-velocity pulsating jets will hit the heat spreader normally (i.e., in the perpendicular direction), thus maximizing the amount of heat dissipated. The high velocity will maximize the amount of heat removed for the amount of air that goes inside the device. This air, saturated with heat, then flows side-wards and exits through the spouts.

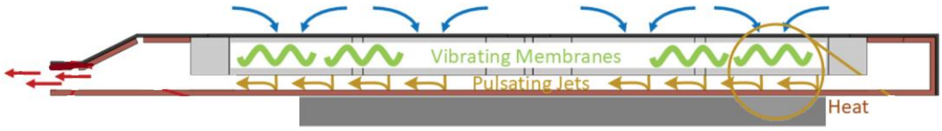


Fig. 3 Jet Impingement

5 Analysis

To study the device in depth, we perform an analysis of the feature element; this element is the building block of the design. The array of these feature elements will build the complete design. Fig 4 shows the feature element having a cantilever with piezoelectric material on the top of the cantilever. Fig 5 shows the **CAD Design** of the device (**Link** to access the design preview).

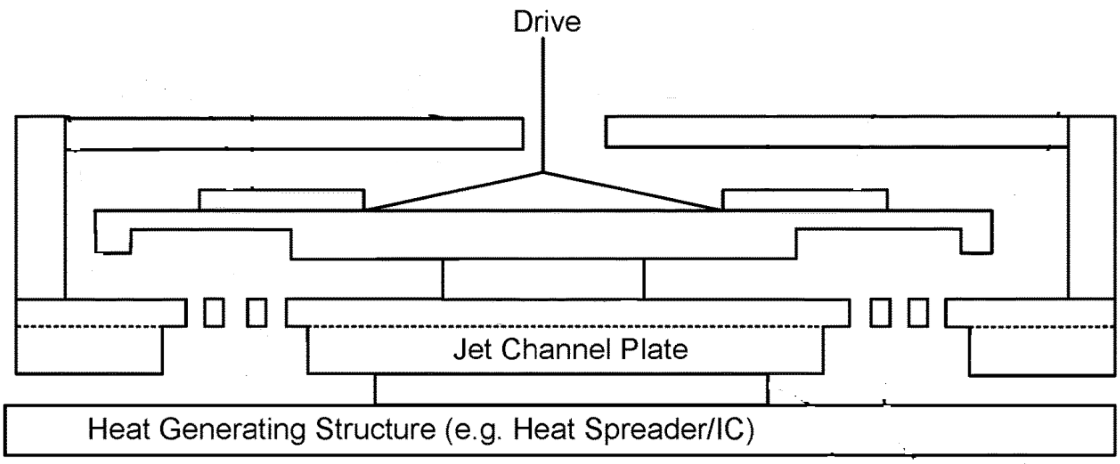
Following parameters will be used for analysis:

V_{jet}: Velocity of air coming out of the orifices

Q : Air flow generated inside the chamber

F : Cantilever Oscillating Frequency
A : Vibration Amplitude
W : Cantilever's Width
L : Cantilever's Length
T : Cantilever's Thickness
W_o: Side length of slotted orifice
S: Distance between the 2 slotted orifice
Nu^{-} : Nusselt number
Re: Reynolds number D_h:
Hydraulic diameter η:
Kinematic viscosity of air

Fig 4. Heating Generating Structure



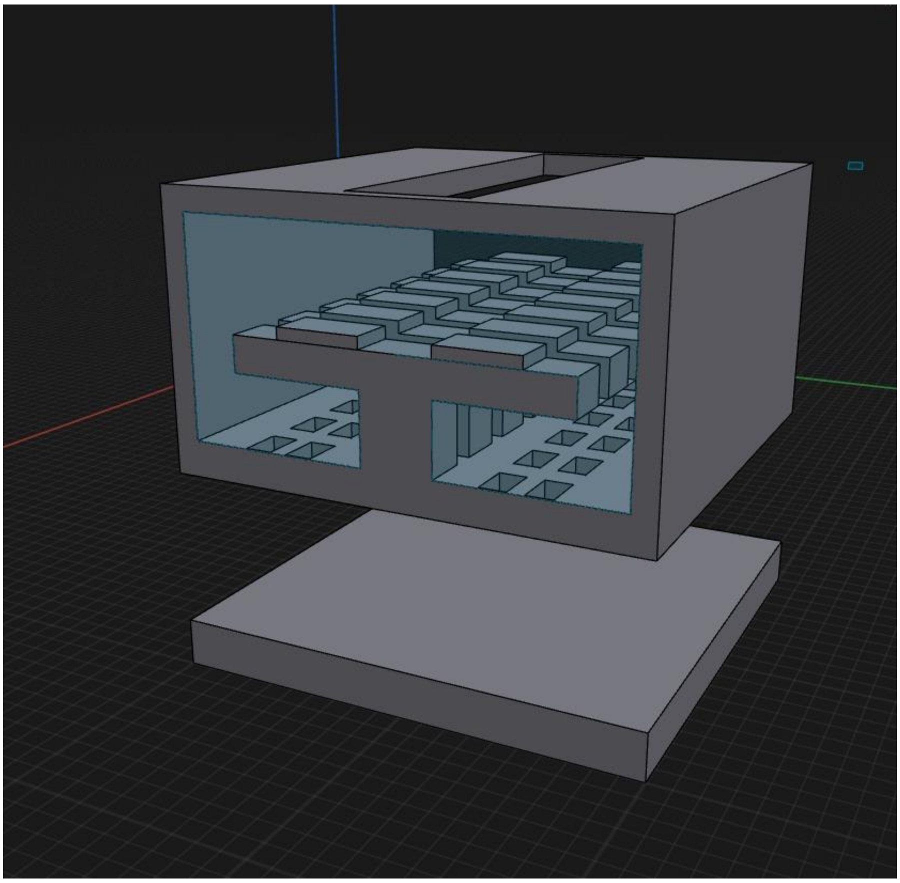


Fig. 5 CAD Design of the device.

5.1 Airflow calculations

To achieve a cooling effect through jet impingement, the air jet coming out from the orifice needs to have some specific velocity. Velocities between 20m/sec to 60 m/sec could lead to better cooling performance. To study the airflow, the following equations [3] can be used:

Following Dimensions of the cantilever will achieve the velocity in the optimal range.

Length of one side of fan = 3 mm Total length of both sides(L)= 6 mm

W(Width of fan) = 250 μm , A(Amplitude)= 10 μm , F(Cantilever Frequency) = 30 kHz(1)

Area of 1 orifice = $50 \times 50\ \mu m^2$ (2)

The Velocity of air-jet through the orifice can be calculated as follows

Volume Displaced per cycle (V_d) = A×W×L

$=(10\ \mu m)\times(250\ \mu m)\times(6\ mm) = 0.015\ mm^3$

Air Flow Rate = (V_d)× (F)

$= (0.015\ mm^3)\times(30\ kHz) = 4.5\times 10{-}7\ m^3/sec$ (3)

Velocity of Airjet= Air Flow rate/ (4×Area of 1 Orifice)

$=(4.5\times 10{-}7\ m^3/sec)/(4\times 50\times 25\ \mu m^2)$

After performing the following calculations, we get :

Velocity of Airjet = 45 m/sec. (4)

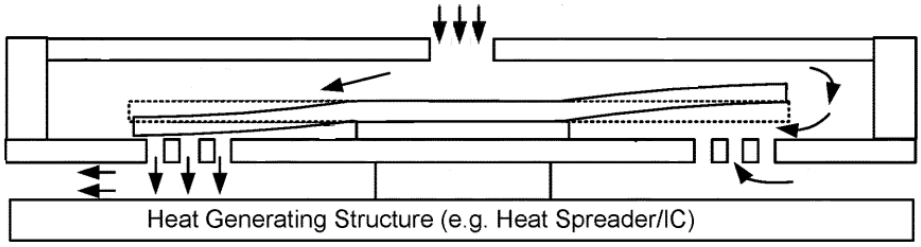


Fig. 6 Airflow due to Vibration

5.2 Jet Impingement cooling

$$q = \tilde{h}A(\Delta T)$$

where:

q is the heat transfer rate (W)

h is the heat transfer coefficient ($W/m^2{\cdot}K$)

A is the surface area (m^2)

ΔT is the temperature difference between exit point of nozzle and heating surface (K)

We will be using Newton's law of cooling. Here the heat coefficient is obtained from the correlation of the Nusselt number [4]. Nusselt number is the ratio of convective to conductive heat transfer across a boundary. When it comes to doing calculations, the geometric features of the jet become very important and will affect the heat transfer. Hence the relation may vary for the rounded, slotted, or array of nozzles.

Our proposed design uses the slotted array nozzle geometry, the following are the correlation [4] corresponding to geometry.

$$\frac{\bar{Nu}}{Pr^{0.42}} = \frac{2}{3} A_{r,o}^{\frac{3}{4}} \left(\frac{2\ Re}{\frac{A_r}{A_{r,o}} + \frac{A_{r,o}}{A_r}} \right)^{2/3} \tag{5}$$

$$A_{r,o} = \left[60 + 4 \left(\frac{H}{2W_o} - 2 \right)^2 \right]^{-1/2} \tag{6}$$

$$A_r = W_o/S \tag{7}$$

$$Re = \frac{V_{jet} * D_h}{\eta} \tag{8}$$

$$\bar{Nu} = \frac{\tilde{h} * Dh}{K} \tag{9}$$

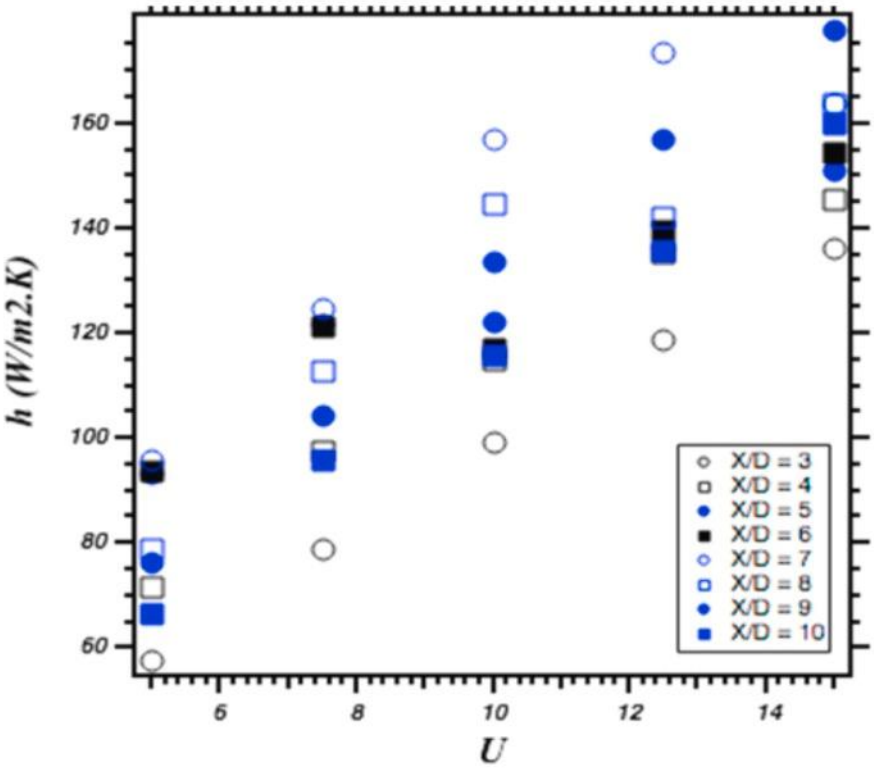


Fig7. Heat transfer distribution at several patterns of velocities [5]

6 Design

The top plate of the device will consist of air vents that will allow the ambient air to enter the device as shown in figure 7. These vents can be covered by a dust-resistant coating to prevent dust particles larger than a particular threshold from entering the device.

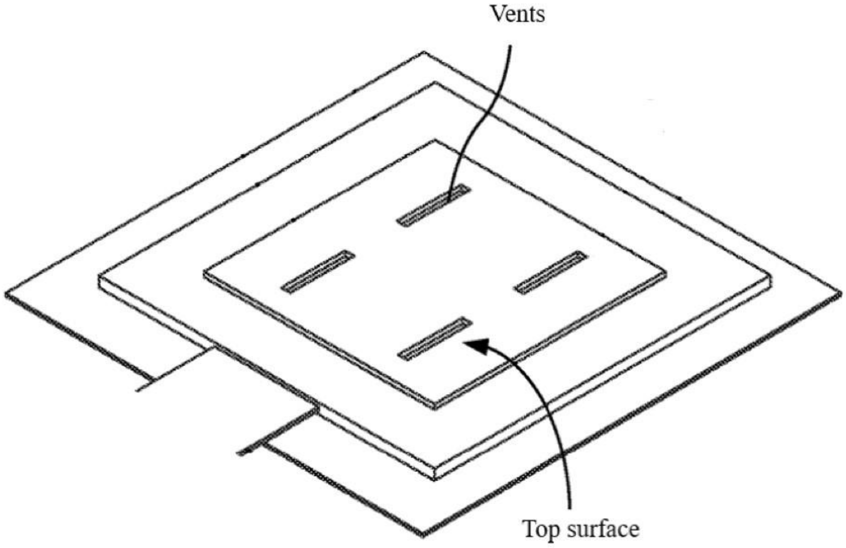


Fig. 8 Top Surface

The top chamber will consist of a cooling element which is typically a MEMS-based membrane. The membrane will include a piezoelectric layer on top of a substrate that will be responsible for the vibrating action.

The middle portion of the membrane will be anchored to a plate to provide support for its vibration motion. The ends of the membrane will undergo a cantilever-like motion .The cavities will be made just above the orifices in order to capture and send greater volumes of air through the orifices during the vibration motion. The cavities will also help in decreasing the mass towards the ends, thus allowing for more rapid vibrations.

The bottom plate will consist of orifices that will direct the airflow toward the bottom chamber, along with an anchor to act as a support structure for the cooling element. The bottom plate should be made of a material having low internal losses. For e.g., Al, Ti, beryllium-copper alloy, monel, aluminum bronze, SUS304, or SUS316.

The high-velocity pulsating jet stream will strike the heat spreader, which can be made of Copper (Cu), to carry the heated air molecules through the spout/outlet. The spout can be made in such a fashion that allows the laminar flow of the hot air to decrease the time between the air entering and exiting the device and thus increasing the efficiency of the device.

The design of the device is optimized for efficient cooling, with the top plate featuring air vents, the top chamber containing the cooling element, the MEMS-based membrane responsible for vibrating and directing airflow, and the bottom plate with orifices that direct the airflow towards the bottom chamber. The high-velocity pulsating jets created by the MEMS-based membrane hit the heat spreader normally, maximizing the amount of heat dissipated and removed from the surface rapidly.

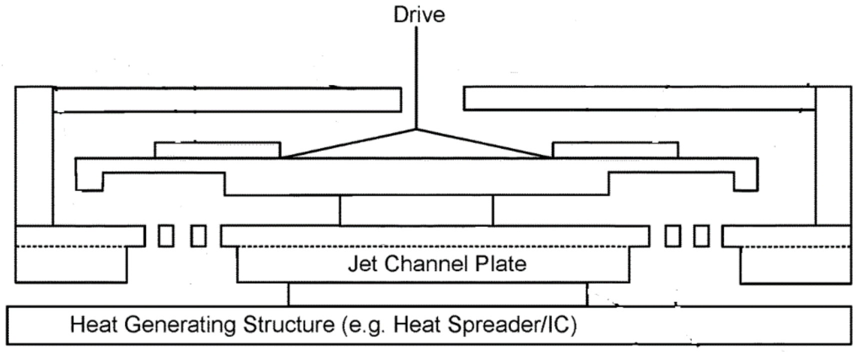


Fig. 9 Cross-sectional View of the Internal Structure

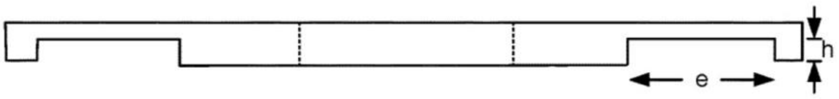


Fig. 10 Structure of the MEMS-based membrane

7 Microfabrication

The microfabrication process of the MEMS-based vibrating membrane Involves the following steps:

1. **Substrate Preparation**: Begin with a silicon wafer as the substrate material. Below are some properties of silicon material

Bulk modulus- 9.8·1011 dyne/cm2

Melting point- 1412 °C

Specific heat -0.7 J g-1°C-1

Thermal conductivity- 139 W m-1°C-1

Thermal diffusivity- 0.8 cm2 / s

Thermal expansion,- linear 2.6·10-6°C -1

The orientation of the material silicon is 100, so that this material should be isotropic. The grade of the material is prime because we need high quality silicon, so that the required mechanical properties should be satisfied for mems fabrication. The Float-Zone method is used to make pure Silicon and the material should be doubly side polished. Deposit a thin layer of silicon dioxide (SiO2) on the silicon substrate using thermal oxidation or chemical vapor deposition (CVD) techniques. Silicon and Silicon Dioxide layer are made into a substrate that is chemically inert and thermally conductive.

A SiO2 passivation layer with a thickness of around 100 nm to 1 μm is used. This thickness provides adequate protection against moisture and chemical reactions while minimizing thermal resistance and maintaining compatibility with MEMS fabrication processes. Perform hydrogen passivation to introduce hydrogen atoms into the silicon lattice and reduce brittleness. Anneal the SiO2-passivated silicon substrate in a hydrogen atmosphere at elevated temperatures (typically around 400-500°C) for a certain duration. This process helps saturate surface bonds with hydrogen atoms, improving mechanical properties and toughness.

The second step in substrate preparation process is:

Begin with a Utilizing Copper as a Heat Spreader due to its excellent thermal conductivity and other advantageous properties. Below are some properties of copper material:

Thermal Conductivity ~401 W/(m·K) at 25°C

Electrical Conductivity ~58 MS/m at 20°C

Melting Point~ 1,085°C (1,984°F)

Density ~8.96 g/cm^3

Specific Heat Capacity ~0.385 J/(g·K) at 25°C

Thermal Expansion Coefficient ~16.5 × 10^-6 /K

Overall, these properties make copper an ideal material for heat spreading applications, where efficient thermal management is crucial for maintaining the performance, reliability, and longevity of electronic devices.

Fig. 11 Microfabrication Process Workflow

2. **Material selection for Substrate and Piezoelectric layer**: The substrate should be chosen such that it has high mechanical strength and a low coefficient of thermal expansion. The piezoelectric layer can be made of Aluminium Nitride (AlN) and Zinc Oxide (ZnO). AlN has a higher thermal stability and can withstand temperatures up to 1000 $^{\circ}$C, whereas ZnO has a lower temperature limit of around 400 $^{\circ}$C. AlN also has high mechanical strength and stiffness, making it less prone to cracking or failure under mechanical stress. ZnO has a higher piezoelectric coefficient compared to AlN, which means the intensity of vibrations will be greater and will improve cooling. However, ZnO is sensitive to humidity, and its performance degrades over time when exposed to humidity. Thus, AlN would be a better choice for the piezoelectric layer. [6] Length of piezoelectric materials =1.4mm . Thickness of piezoelectric materials =0.3mm

3. **Cleaning the substrate**: Clean the silicon dioxide substrate thoroughly to remove any contaminants or residues that could affect the film deposition process. Standard cleaning methods involve using solvents like acetone, isopropyl alcohol, and deionized water, followed by drying with nitrogen gas. The Substrate is etched using wet etching to remove unwanted material and create the desired structure as shown in Fig. Wet etching is commonly used for Silicon based substrates and since we don't require a very complex etch profile, wet etching is a cost-effective option. We will use the photoresist (polymethyl methacrylate) and photomask(chromium) compounds for etching the bottom SiO2 layer the process is followed by photolithography and then dry etching using reactive ion etching (RIE) which is compatible with photolithography. The photomask should be made with proper length, width and thickness, so as to ensure proper construction of this curve.

4. **Deposition of Piezoelectric Material**: Deposit a layer of aluminum nitride (AlN) onto the hydrogen-passivated silicon substrate using techniques such as Pulsed Laser Deposition (PLD). PLD offers excellent control over film thickness, Very fine control over film growth. High purity and high density of the films. With Certain assumptions or trial and error in the calculations, we can set both the

membrane and AlN in same frequency.

Fig. 12 Deposition of Piezoelectric Material

5. **Photolithography**: Exposure: A mask is used to expose the deposited AlN layer with UV rays such that blocks of the piezoelectric layer can be formed, which can contract and expand independently. We utilize negative photoresist, specifically SU-8, along with photomasks(chromium) Developing: Solutions such as Sodium Hydroxide (NaOH) or Potassium Hydroxide (KOH) can be used for developing the piezoelectric layer after exposing.

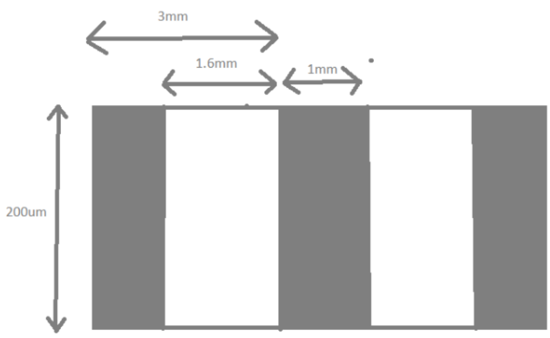
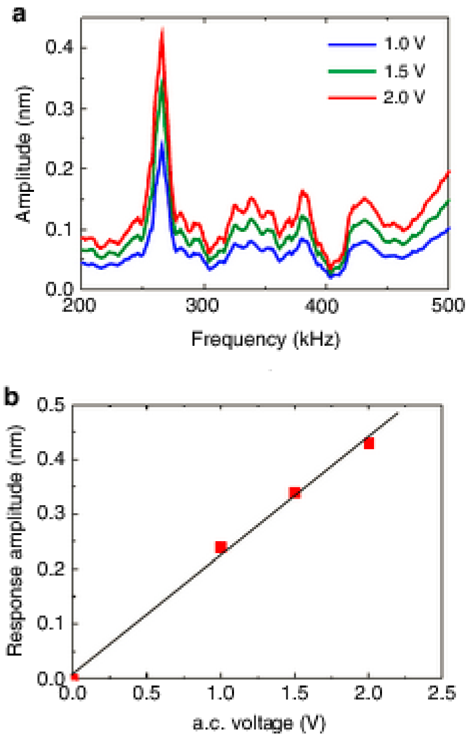


Fig. 13 Photolithography

8 Graphs

With Certain assumptions or trial and error in the calculations, we can set both the membrane and AlN in same frequency.



9 Key Components of MEMS-based Cooling System

Microfluidic Channels Microscale channels that enable precise fluid flow and heat transfer for effective cooling.

Micropump and Valves Miniaturized pumps and valves that precisely control the movement of coolant fluids.

Microelectronic Sensors Embedded sensors that monitor temperature, pressure, and other critical parameters for feedback control.

Microfabricated Heat Sinks Compact, high-surface-area heat exchangers that efficiently dissipate heat from electronic components.

10 Advantages of MEMS-based Cooling over Traditional Methods

Size and Footprint: MEMS-based cooling systems are significantly smaller and more compact compared to traditional heat sinks and fans, enabling sleeker and more space-efficient device designs. By taking into consideration of any array of 8 MEMS-based fan in our cooling system and giving an spacing of 250 microns between each fan, we have calculated the dimensions of MEMS-based cooling system as **4.65mm* 8.4mm* 2.85mm** , but the dimensions of traditional fan are approximately **120mm * 140mm * 10mm** , which is significantly larger as compared to our MEMS-based cooling system.
Energy Efficiency MEMS coolers operate on low power consumption, making them more energy-efficient than bulky mechanical cooling solutions, reducing overall system power requirements.
Precise Control MEMS technology allows for highly precise and dynamic temperature control, enabling optimal cooling tailored to specific device needs and operating conditions.
Reliability MEMS-based cooling systems have no moving parts, reducing the risk of mechanical failure and increasing overall system reliability and lifespan.

11 Thermal Management Capabilities of MEMS-based Cooling

Heat Dissipation MEMS-based cooling systems can effectively dissipate heat from electronic components, maintaining optimal operating temperatures and preventing thermal-related failures.
Precise Temperature Control Leveraging micro-scale sensors and actuators, these systems offer precise, dynamic temperature regulation for sensitive electronic devices and systems.
Energy Efficiency MEMS-based cooling solutions are highly energy-efficient, consuming less power compared to traditional cooling methods, making them ideal for portable and battery-powered applications.
Compact Design The miniaturized nature of MEMS components allows for the development of ultra-compact cooling systems that can be easily integrated into a wide range of electronic devices.

12 Future Scopes for MEMS-based Active Cooling

Microelectronics Cooling: MEMS-based active cooling systems can precisely control heat dissipation in high-performance laptops and enabling more efficient thermal management.

Medical Device Cooling: Compact MEMS coolers can be integrated into advanced medical devices like implants and diagnostic tools, allowing for more precise temperature regulation and improved performance.

Aerospace and Avionics: MEMS-based cooling systems can be used in aircraft and spacecraft to manage thermal loads of sensitive avionics and electronic systems in harsh environments.

Automotive Electronics: MEMS coolers can be employed in vehicles to provide localized cooling for increasingly complex automotive electronics and power components, enhancing reliability and efficiency.

Optoelectronics: High-power optoelectronic devices such as lasers and photodetectors require efficient cooling to maintain performance and reliability. MEMS-based active cooling systems can provide precise thermal management for these devices, enabling advancements in applications such as telecommunications, laser machining, and lidar systems.

Consumer Appliances: Beyond electronics, MEMS-based active cooling systems could be integrated into household appliances such as refrigerators, air conditioners, and cooking appliances to improve energy efficiency and performance. These systems could enable precise temperature control and reduce overall energy consumption in residential and commercial settings.

13 Conclusion

In conclusion, MEMS-based active cooling systems offer a transformative solution to address the limitations of traditional cooling methods. By leveraging the unique capabilities of microelectromechanical systems, these innovative systems enable precise, efficient, and responsive thermal management, paving the way for enhanced performance and reliability in a wide range of applications. The key advantages of MEMS-based cooling, such as compact size, high power density, and dynamic control, make it a superior choice compared to bulky, energy-intensive conventional systems.

As **technology** continues to evolve, we can expect to see even greater advancements in thermal management capabilities, **opening** new possibilities for high-performance electronics, aerospace, and beyond. While some challenges remain in the scalability and cost-effectiveness of MEMS-based cooling, the future looks bright. With ongoing research and innovation, these obstacles will be overcome, further driving the adoption of this transformative **technology,** and ushering in a new era of efficient and adaptable thermal management solutions.

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