Design and Development of ultra-fast, real time temperature measurement setup for embedded systems

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Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements.

Submitted by: Allola Nikhil Reddy & Hanuman Meena
December 2017

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It is certified that the declaration made by the student is correct to the best of my knowledge and belief.

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Preface

This report on **"Design and Development of ultra-fast, real time temperature measurement setup for embedded systems"** is prepared under the supervision of Dr. M.Anbarasu, Associate Professor, Electrical Engineering, IIT Indore.

Throughout this report, detailed description of the theoretical concepts used to design the temperature measurement setup is provided. The designed model is tested against different materials & thicknesses and the results are presented in a clear and concise manner. We have also added tabular and graphical figures to make it more illustrative.

Acknowledgements

We would like to thank our B.Tech Project supervisor **Dr. M.Anbarasu** for guiding us thoughtfully and efficiently throughout this project, giving us an opportunity to work at our own pace while providing us with useful directions whenever necessary. He gave us an opportunity to discover and work in such an interesting domain. His guidance proved really valuable in all the difficulties we faced in the course of this project.

We are really grateful to Mr. Nishant Saxena for his constant support and contribution throughout the project. He provided valuable guidance and help us understand the concepts. We would also like to thank Mr. Ashish Kumar Shukla for his guidance with COMSOL Multiphysics. He helped us in getting started with the software and provided useful directions to proceed along whenever necessary.

We offer our sincere thanks to everyone who else who knowingly or unknowingly helped us complete this project.

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Abstract

The Project work involved the simulation of different models on COMSOL multiphysics software and the study of various temperature measuring techniques. This included the investigation of different models to identify the best suitable one regarding the response time of the measurement. Additionally, an appropriate pattern for the thermometer layer was developed to optimize the resistance to be measured.

The temperature measurement response time was found to be influenced mainly by the convective heat transfer coefficient of the materials used and the thickness of isolation layer electrodes between the test material and the thermometer layer. This indicates that these thicknesses should be kept as less as possible but are generally limited by some non-ideal factors like physical damage threshold. Materials with higher thermal conductivity allowed faster cooling which means better time resolution of the measurement and poor response time while lower thermal conductivity materials allowed faster heating meaning faster response times and poor time resolution. A detailed study about the materials is done to chose better design.

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Chapter 1

Introduction

This chapter highlights the background and motivation for the project. The problem statement of the project has been described and the importance of the results is also clearly portrayed. Towards the end of the chapter the objectives and expectation from this project are also outlined.

1.1 Background

Temperature measurement in today's industrial environment encompasses a wide variety of needs and applications. While the temperature is generally sensed by humans as "hot", "neutral", or "cold", Engineering requires precise, quantitative measurements of temperature in order to accurately control a process. To meet this wide array of needs the process controls industry has developed a large number of sensors and devices to handle this demand. From a thermodynamics perspective, temperature changes as a function of the average energy of molecular movement. As heat is added to a system, molecular motion increases and the system experiences an increase in temperature. It is difficult, however, to directly measure the energy of molecular movement, so temperature sensors are generally designed to measure a property which changes in response to temperature. The devices are then calibrated to traditional temperature scales using a standard. There are many temperature measurement techniques developed for different applications focusing on features like high accuracy, high stability, high precision, high operating range etc. Recently, there has been a growing interest in developing techniques with fast response time and a good spatial resolution. These kinds of technologies were earlier used in measuring temperatures during pulsed laser irradiation and other fibre-optic based applications.

One such application is in investigation of the thermally activated phase changes in phase change materials. Phase change materials, can be induced to switch reversibly between their amorphous and crystalline states by heating at a nanosecond scale. There has been an immense amount of research going on this memory to understand the process and to make it more efficient. To understand the basic process, there is a need for ultra-fast temperature measurements. The technology used in this project is based on thin film resistance thermometer detectors which will be discussed in next chapters.

1.2 Objective

As per the above discussion, the objective thus is the Development of an ultra-fast temperature measuring technique and testing it with phase change materials. The above objective has been divided into following goals:

- To study different technologies and identify the right one for this application.
- To understand the physics behind the working of the technology, design a model and simulate the design on software.
- To study the possibilities of using various materials
- To test the developed model with phase change materials.

Chapter 2

Literature Review

This chapter discusses the various concepts used during the course of this project. The chapter starts with discussion on phase change materials, followed by the temperature measuring technologies, a comparison between them. This is then followed by a discussion on thin film RTDs and other interesting technologies.

2.1 Phase Change Materials

Commonly referred to as Ovonic memory, the concept was first proposed by Stanford Ovshinsky in 1968, it exploits the fact that certain alloys of group V or group VI elements, known as phase change materials, can be induced to switch reversibly between their amorphous and crystalline states with an electrical current, and that the electrical resistance of these two states is substantially different.

When a phase-change material in its amorphous high-resistance state is heated to just above its glass transition temperature by an applied electrical pulse (set operation), increased mobility of its atoms allow them to rearrange into a more energetically favourable crystalline state. To switch it back to the amorphous state, the material is heated to above its melting temperature with a voltage pulse of greater magnitude (reset operation) causing it to liquefy and then rapidly cool (by contact with its surroundings) to quench it in the amorphous state[7]. Because the amorphous and crystalline states have very different electrical resistances, the information recorded can be read easily. The architecture of a conventional memory cell consists of a phase change material sandwiched between two conducting contacts[4] whose temperature measurement is one of the main aim of this project.

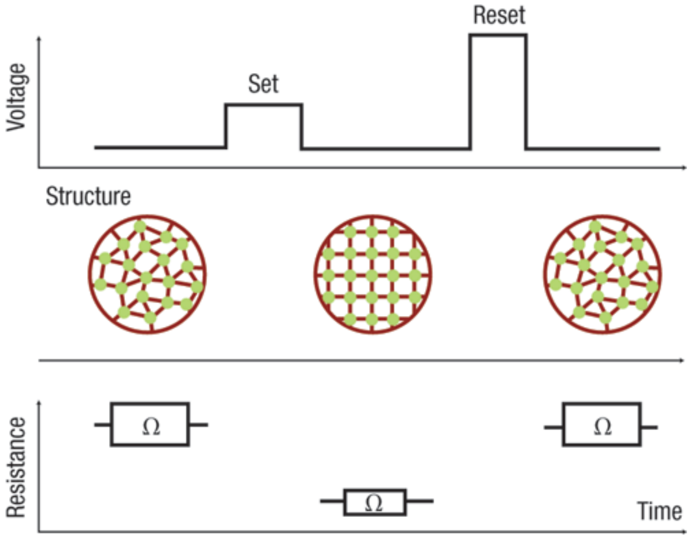

Fig. 2.1 The Operation Principle of a memory device based on phase changes[7]

2.2 Comparison of different technologies

The first task of the project was to identify a promising technology for measuring temperatures. Out of all the previously used techniques, thermocouples have very high operating ranges but were comparatively slow. Thermistors have better sensitivity but the operating ranges are found to be too low. Other technologies like the fibre optic based Fabry-Perot sensors had response times in the range of few microseconds but have poor spatial resolution in comparison to thin film Resistance thermometer detectors (RTDs). The next sections will highlight interesting technologies and discuss their advantages.

Technology	dX (μm)	dT(K)	dt(μs)
Infrared Thermography	10	10^{-1}	10
Thermoreflectance	10^{-1}	10^{-2}	10^{-1}
Micro-thermocouple	10^{-2}	10^{-1}	10
Near field scanning optical microscopy	10^{-2}	10^{-1}	10
Optical Interferometery	10	10^{-5}	10^{-3}

Table 2.1 The Time, Spatial and temperature resolution of various methods used to measure temperature[2]

2.3 Fabry-Perot Interferometer

Eric Pinet in 2009 has developed a Fabry-perot fiber-optic sensor which is capable of measuring surface temperatures at an ultra-fast scale[5]. A tiny chip of a semiconductor material with high thermal refractive index dependence and two semi reective surfaces constituting an F-P cavity is used to measure temperatures. Any change in temperature is reflected in OPD of the F-P sensor which is calculated to determine the temperature. With a response time of around $5\mu s$, this is one of the most interesting technologies to measure ultra-fast temperature changes. The working principle of this interferometer is presented in Figure 2.2

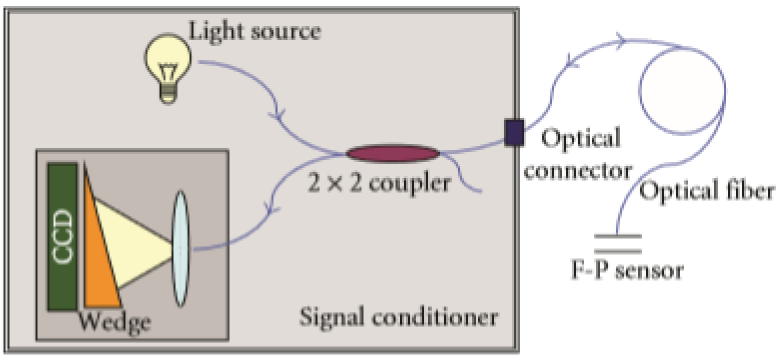

Fig. 2.2 The Operation principle of Fabry-Perot Interferometer

2.3.1 Advantages and disadvantages

The one main advantage when working with fiber optics is that light conned in the optical ber core is not aected by any electromagnetic interference (EMI) which means they are suitable to work in challenging conditions where conventional electrical sensors fail. Applications of this type sensors include Microwave Owens, MRI scan, etc,. The Disadvantage is that the spatial resolution is limited by the diameter of the fibre optic cable used. Also, these sensors are best fit in optical domain and are not desired in optical domain.

2.4 Resistance Thermometer Detectors (RTDs)

An RTD (resistance temperature detector) is a temperature sensor that operates on the measurement principle that a material's electrical resistance changes with temperature. By supplying an RTD with a constant current and measuring the resulting voltage drop across the resistor, the RTD's resistance can be calculated, and the temperature can be determined. Temperature sensitive materials used in the construction of RTDs include platinum, nickel, and copper; platinum being the most commonly used. Important characteristics of an RTD include the temperature coefficient of resistance (TCR), the nominal resistance at 0 degrees Celsius, and the tolerance classes. The TCR determines the relationship between the resistance and the temperature. The nominal resistance of the sensor is the resistance that the sensor will have at 0 degrees Celsius and finally the tolerance class determines the accuracy of the material.

In addition to different materials, RTDs are also offered in two major configurations: wire wound and thin film. Wire wound configurations feature either an inner coil RTD or an outer wound RTD. An inner coil construction consists of a resistive coil running through a hole in a ceramic insulator, whereas the outer wound construction involves the winding of the resistive material around a ceramic or glass cylinder, which is then insulated.

2.4.1 Thin Film RTDs

The thin film RTD construction features a thin layer of resistive material deposited onto a substrate. Thin film RTDs has advantages over the wire wound configurations. The main advantages include that they are more rugged, vibration resistant, and can be fabricated in smaller dimensions that lead to better response times and packaging capabilities. For a long time wire wound sensors featured much better accuracy. Thanks to recent developments, however, there is now thin film technology capable of achieving the same level of accuracy.

Working

An RTD takes a measurement when a small DC current is supplied to the sensor. The current experiences the impedance of the resistor, and a voltage drop is experienced over the resistor. Depending on the nominal resistance of the RTD, different supply currents can be used. To reduce self-heating on the sensor the supply current should be kept low. In general, around 1mA or less of current is used. The RTD can be connected in different configurations with each having its own applications and advantages. Most traditional RTD operation is based upon a linear relationship between resistance and temperature, where the resistance increases with temperature.

2.4.2 Advantages and Disadvantages

Some of the advantages of thin film RTDs include accuracy, precision, long-term stability, and good hysteresis characteristics. Even beyond these, they have an advantage of smaller dimensions, better response times, vibration resistance, and relative inexpensiveness. They have a simple structure and are easy to fabricate with test surface is one advantage that makes them the most suitable for this applications. Thin film-RTDs are also proven to achieve ultra-fast scale response times [3].

2.5 What is Response time of a measurement?

There are many definitions for the response time of the measurement. Some consider it same as the time constant while some as Rise time and some as Settling time. So, it is better to define response time before proceeding further. The Response time of a measurement is defined as the the time taken by the output to reach from 10% of its final value to 90% of its final value.

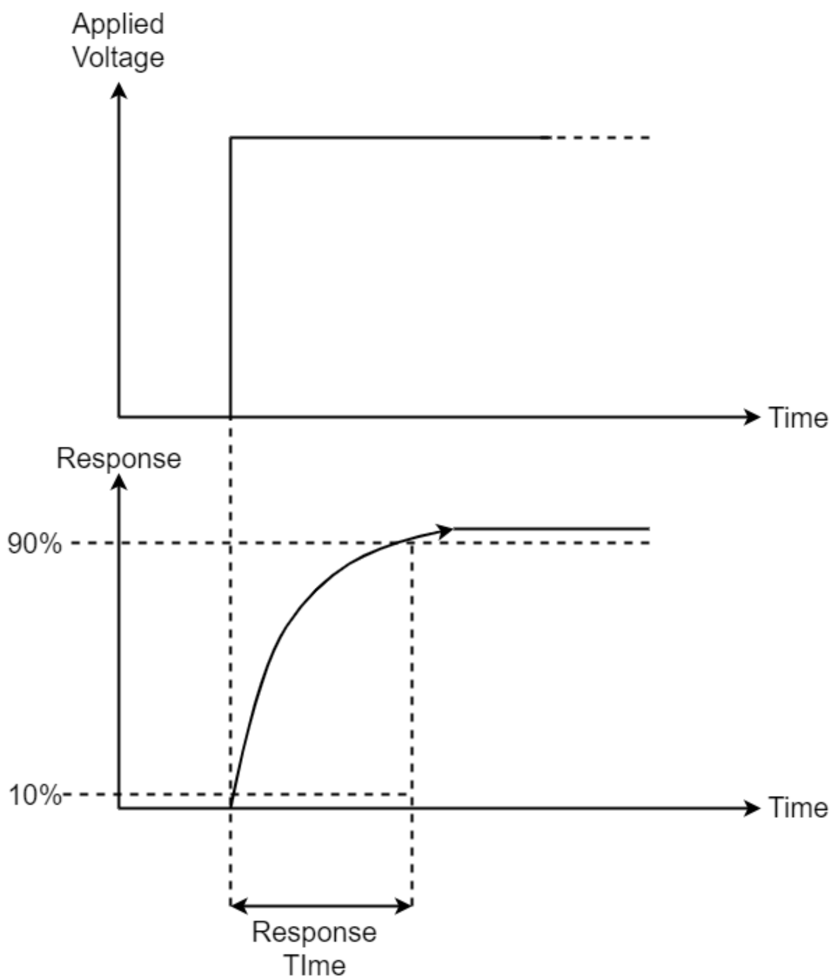

Fig. 2.3 What is Response time of a measurement?

Chapter 3

Design of a Model on COMSOL Multiphysics

In this chapter, we will go through design and implementation of the thin film RTD on COMSOL Multiphysics software. This includes discussion on the assumptions, boundary conditions and other COMSOL features used while performing simulations.

3.1 Design of the model

The next step of the study after drawing a conclusion on the technology is to design a model and understand the physics behind it to modify the model and further improve the response time. The COMSOL Multiphysics software is used to simulate the design. It is a general-purpose software platform, for modelling and simulating physics-based problems. It allows the users to model across multi physics with wide range of material and physics libraries. Almost all physical phenomena can be described by partial differential equations(PDEs) and it is very easy to solve this PDE for simple geometries but it is EXTREMELY DIFFICULT to solve PDE for complex geometries by hand. COMSOL uses finite element method to solve complex PDEs by meshing the geometry into a collection of finite elements. The governing PDEs are satisfied in each local element. The original PDEs (called strong form) are formulated to a weak form, which reduces the spatial derivative order by 1 and the FEM tries to find solutions in a larger function space for a weak form rather than a narrow one for a strong form on an element.

A complex model is designed on COMSOL where a test layer is sandwiched between two electrodes with a thermometer layer fabricated under the cell. An isolation layer is used to electrically isolate the electrodes from the thermometer and to avoid chemical reaction of thermometer with electrodes at any temperature. This design is shown in 3.1

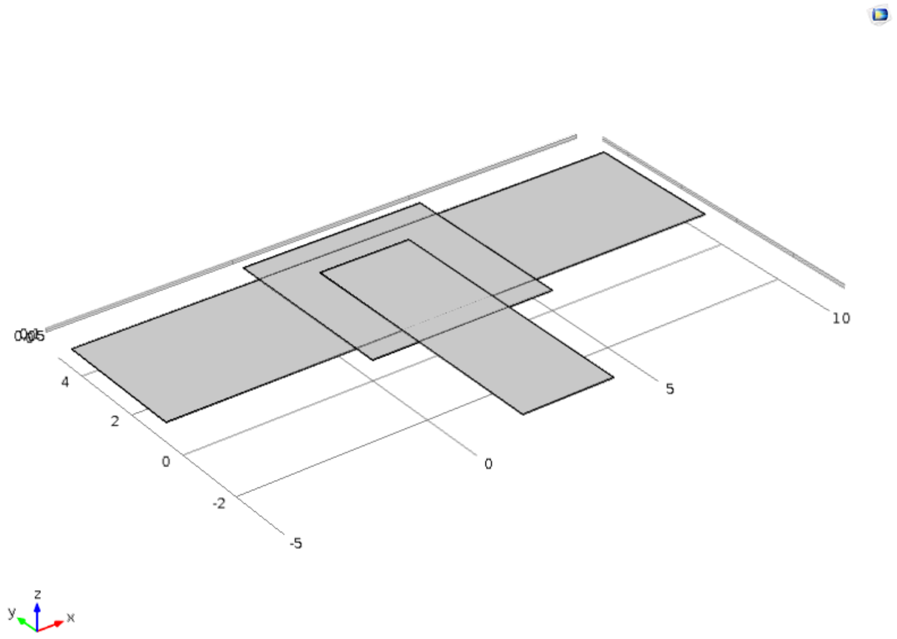

Fig. 3.1 Isometric View

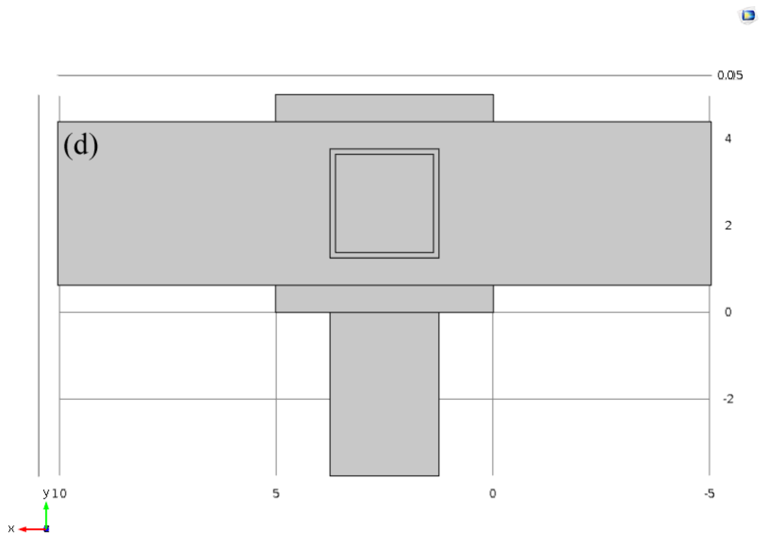

Fig. 3.2 Bottom View

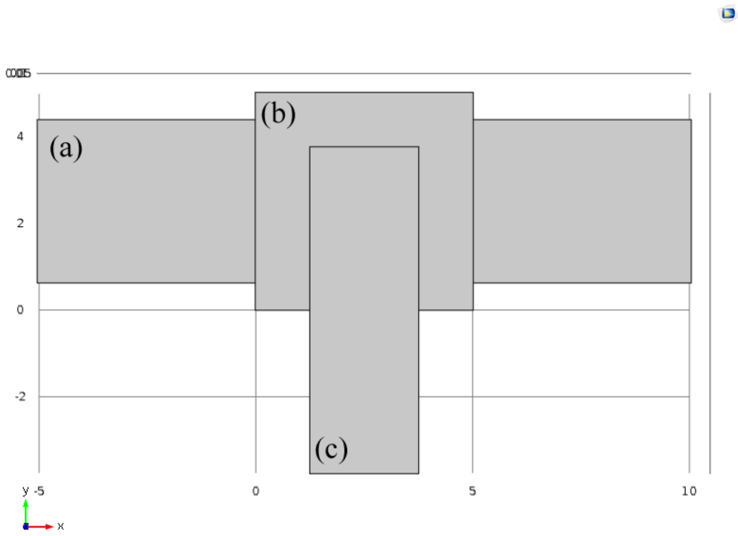

Fig. 3.3 Top View

3.2 Assumptions

Parameter	Value(Units)
Ambient Temperature	293.15(K)
Ambient pressures	1(atm)
Reference Temperature	293.15(K)
Reference Resistivity of Platinum	10.6×10^{-8} (Ω.m)
Reference Resistivity of Tungsten	5.6×10^{-8}(Ω.m)
Reference Resistivity of Silicon nitride	1×10^{8} (Ω.m)
Resistivity temperature coefficient of Pt	0.003927(1/K)
Resistivity temperature coefficient of W	0.0045(1/K)
Resistivity temperature coefficient of Si_3N_4	1×10^{-10}(1/K)

Table 3.1 Parameters used in Simulations

All the Resistivity values are sourced from hyperphysics[hpw]

- Heat transfer by radiation is assumed to be negligible as the temperatures of the model are considered to be low for the entire time.
- External natural convection is assumed.

- Thermal expansion is assumed to be negligible.
- It is also assumed that none of the surfaces are thermally isolated and that all surfaces are open to surroundings.

3.3 Boundary Conditions

The Bottom electrode as seen in Figure 3.2 is made ground and a voltage pulse as shown in 3.4 is applied on the top electrode. The rise time and fall time of the applied voltage are kept at 1ns for all the simulations while the hold time is increased from as low as 1.5 ns to 10 µs and the response of thermometer is noted.

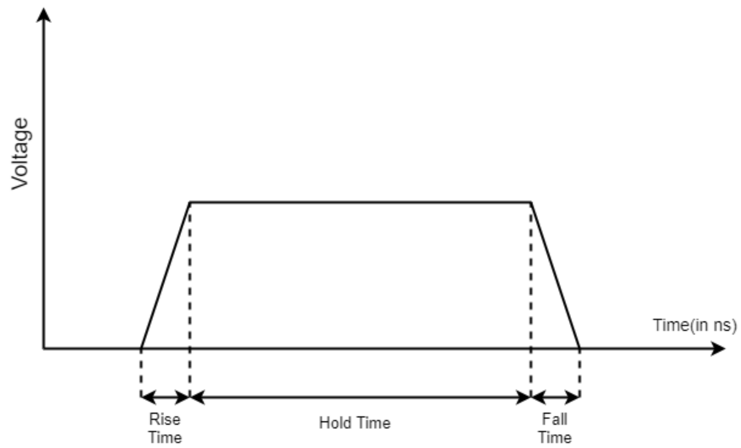

Fig. 3.4 Voltage pulse applied on the boundary C

Since it is assumed that the heat transfer with the surroundings happen only by external natural convection, the characteristic length for each boundary is calculated and used to apply heat flux boundary conditions for all the boundaries separately.

3.4 Mesh

Mesh generation is the practice of generating a tetrahedral (tets), hexahedra (bricks), triangular prisms (prisms), or pyramids grid that approximates a geometric domain. Tetrahedral elements are the default element type for most physics within COMSOL Multiphysics. Tetrahedral are also known as a simplex, which simply means that any 3D volume, regardless of shape or topology, can be meshed with tets. They are also the only kind of elements that can be used with adaptive mesh refinement. The domain is discretized with finite elements and the finite element method is used to estimate solutions of physical problems.A physics controlled sequence type mesh with a coarse predefined size setting is used. Figure 3.5 shows how the model is meshed. An increased number of elements result in more degrees of freedom and longer computational time with improved accuracy.

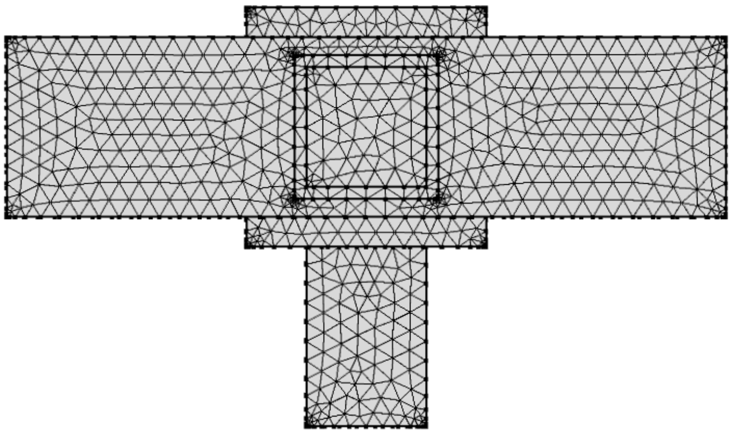

Fig. 3.5 Distribution of the mesh over the model

For the final simulation where the accuracy is important, a user controlled sequence with free tetrahedral type mesh is used. The minimum element size is kept shorter than smallest edge to avoid any errors.

3.5 Post Simulation - Result Extraction

Since temperature that needs to be calculated is measured by measuring the resistance, we evaluated temperature using volume average of a domain

Parameters such as the current flowing between the terminals, resistance between the terminals are calculated using the global evaluation function. The expression of conductance under terminals drop down is used. This function calculates the conductance between the ground and terminal voltage applied to the model.

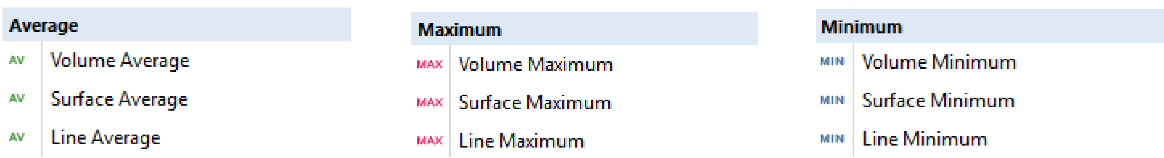

Fig. 3.6 Functions in COMSOL that are used for calculation of temperature.

Chapter 4

Results & Discussion

This chapter discusses few important investigations: the investigation of design, material choices, thickness of different layers and designing a thermometer pattern to determine its resistance.

4.1 Design

The Aim of this study is to design a suitable model to measure temperature at an ultra-fast scale. For this purpose many different models were designed and simulated, two of the most interesting ones are presented in this report. The assumptions and boundary conditions that are mentioned in the previous chapter are applied. The Design in which the thermometer and the isolation are dimensionally bigger than test layer led to a non-uniform distribution of temperature over the thermometer layer as shown in Figure 4.1 and Figure 4.2. This is not desired because it may not give us the desired output and may damage the material in long term. From the modified design shown in Figure 4.3, where the dimensions of thermometer and isolation are less than that of the test layer, we were able to overcome this. Simulations were initially done on both the designs but due to better performance of the second design, It is used for further studies.

Design - I

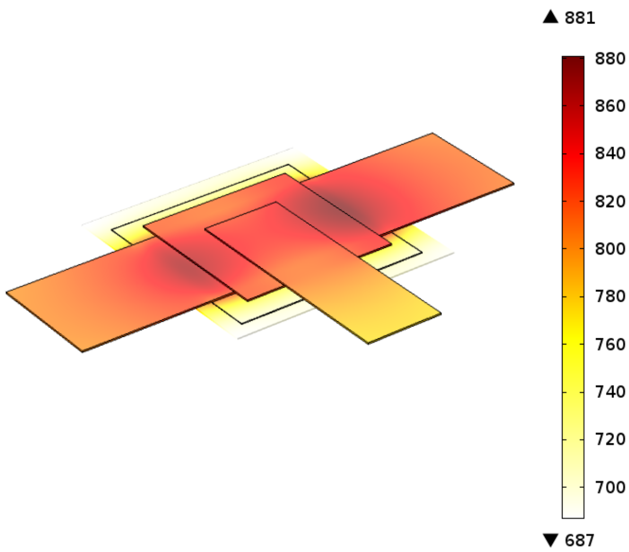

Fig. 4.1 Design - I - Isometric View - Top

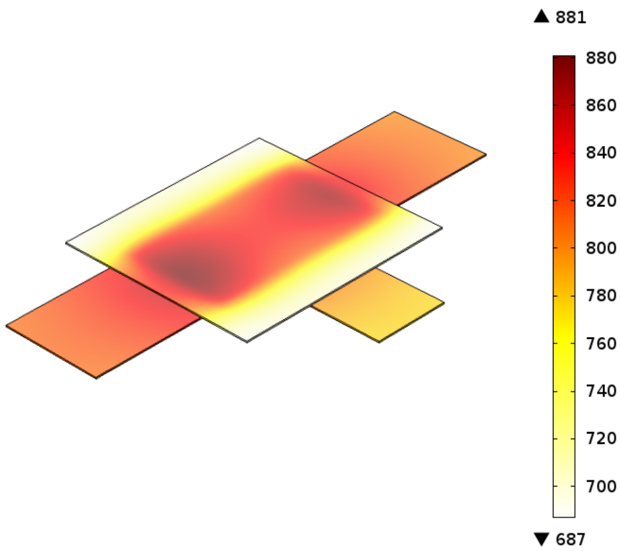

Fig. 4.2 Design - I - Isometric View - Bottom

Design - II

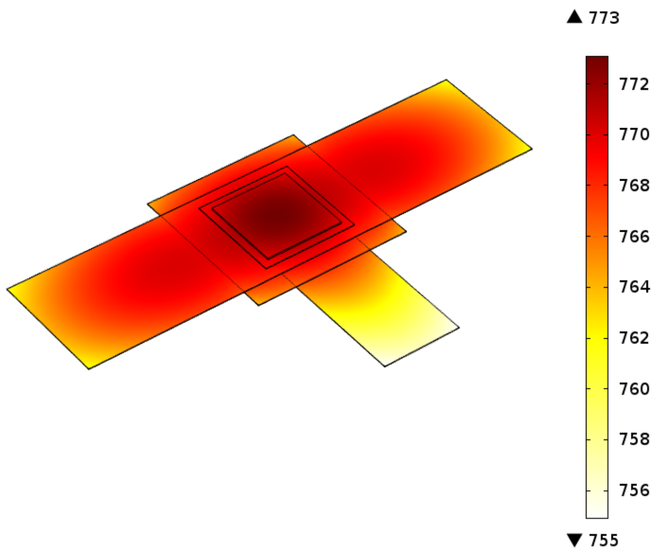

Fig. 4.3 Design - II - Isometric View - Bottom

4.2 Effect Of Change in Materials

The aim of this investigation basically is to evaluate the possible options of the materials and produce a clear procedure how to design the device in a good way so that a better temperature response time can be achieved for the this technique. All measurements regarding the temperature have been made at room temperature and atmospheric pressure conditions. Other key parameters changes are mentioned for every investigation. About four different investigations have been performed in this part to get all important information needed, as presented below.

4.2.1 Test Material

The main objective of this project is to simulate the model using any one of the phase change material such as $Ge_2Sb_2Te_5$. Although COMSOL is widely known as a highly flexible numerical model, it has not been fully explored yet as a tool for simulating phase change materials. Instead, a metal, Tungsten is used as the test material throughout the project. For further research to study the behaviour of phase change materials, a material library can be developed and used instead of a metal or a semiconductor.

4.2.2 Thermometer

Of all materials currently utilized in the fabrication of thermo-resistive elements, platinum has the optimum characteristics for service over a wide temperature range. Platinum resistance thermometers are the international standard for temperature measurements between the triple point of hydrogen at 13.81 K and the freezing point of antimony at 630.75 C. This is because of stable non-reactive nature having linear resistance temperature relationship over a wide range of temperature which is discussed in later sections of this chapter. Hence, platinum was used for all the investigations.

4.2.3 Isolation

An isolation layer, e.g., SiO_2 or Si_3N_4, may be necessary between the thermometer and surface layers to electrically isolate the thermometer and/or avoid chemical interactions between these layers. For this investigation, two materials are chosen for isoation material and simulations are performed using Tungsten test layer. Figure 4.4 shows the plot of temperature(K) of the thermometer against time in microsecond scale.

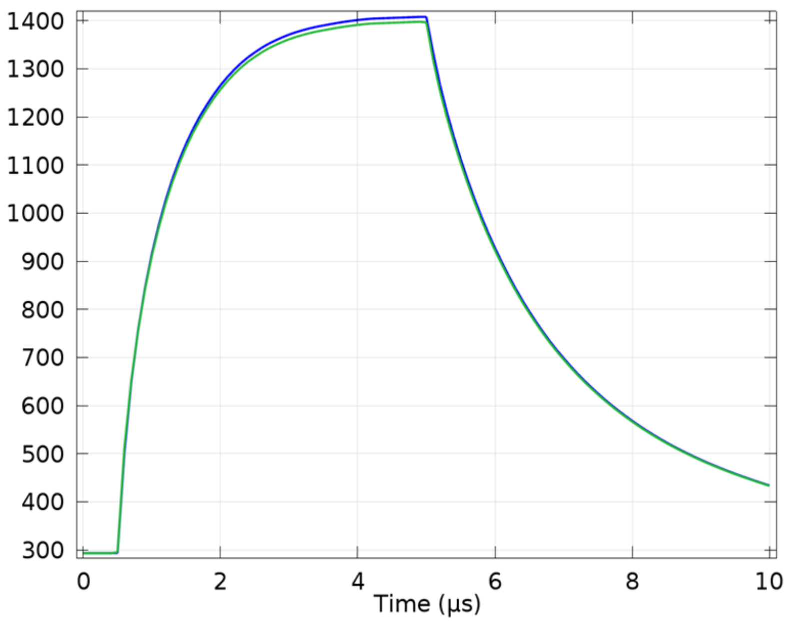

Fig. 4.4 Variation of Temperature with time for different Isolation materials

From the result, one can say that, it is possible to use any one of the two for isolations without affecting much the response time or minimum voltage required as long as its thickness is kept less than 50nm which is explained later sections. In other words, trying to improve response time by simply changing the isolation will not make significant difference.

4.2.4 Electrodes

The purpose of this investigation is to see the behaviour of thermometer if the electrode material is varied and to make a comparison between the response times for different materials. The response time for different materials i.e., Platinum, Aluminum, Titanium have been investigated. The plot of temperature as a function of time for all three materials is shown in Figure 4.5. The response time lies in the range of 1.2µs to 2.1µs for all materials.

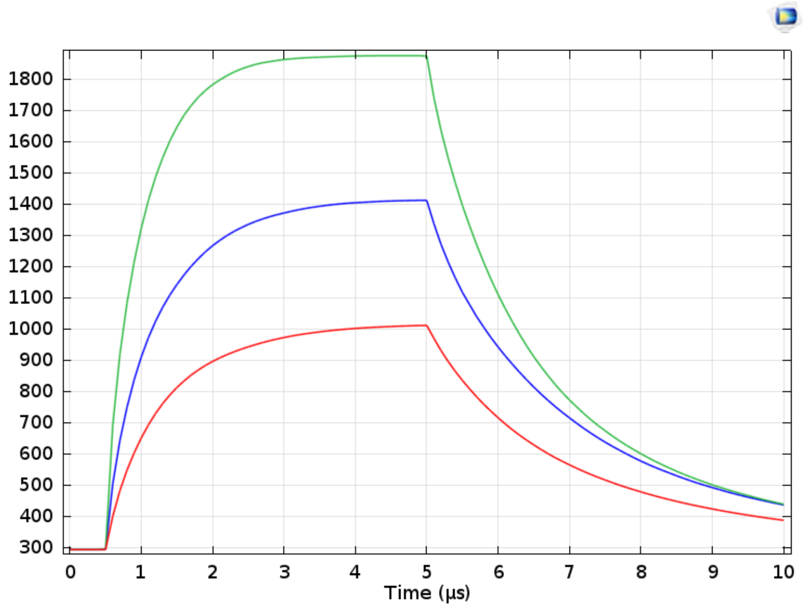

Fig. 4.5 Variation of Temperature with time for different Electrode materials

Material	Response time
Aluminum	1.2µs
Platinum	1.7µs
Tungsten	2.1µs

Table 4.1 Electrode Material VS Response Time

It is noticed that the response time depends mainly on the thermal conductivity. The Material with higher thermal conductivity has faster response time. It should also be noted that though Aluminum has faster response time, it may not be desirable for measuring temperatures above it's melting point at 660.3 °C.

4.3 Thickness

The objective of this investigation is to check the effect of thickness on response time. The material settings used for this investigation were: Tungsten as top/test material, Si_3N_4 as Isolator, Platinum as electrodes and thermometer. The thickness of the thermometer, isolator and electrodes are varied and results are discussed.

4.3.1 Thermometer

Figure 4.6 shows that the temperature response time is in the range of 1.7 to 2 us for thicknesses 10nm, 20nm, 30nm, 50nm, 100nm. But, it is difficult to draw conclusion about appropriate thickness since the temperature response time does not seem to have a big correlation with the thickness of thermometer. Therefore, one can use any thickness option as far as response time is concerned. However, since the resistance of the thermometer is inversely proportional to the thickness of thermometer. The thickness should be a concern of resistance to be measured. The range of resistance will decide the sensitivity of the measurement.

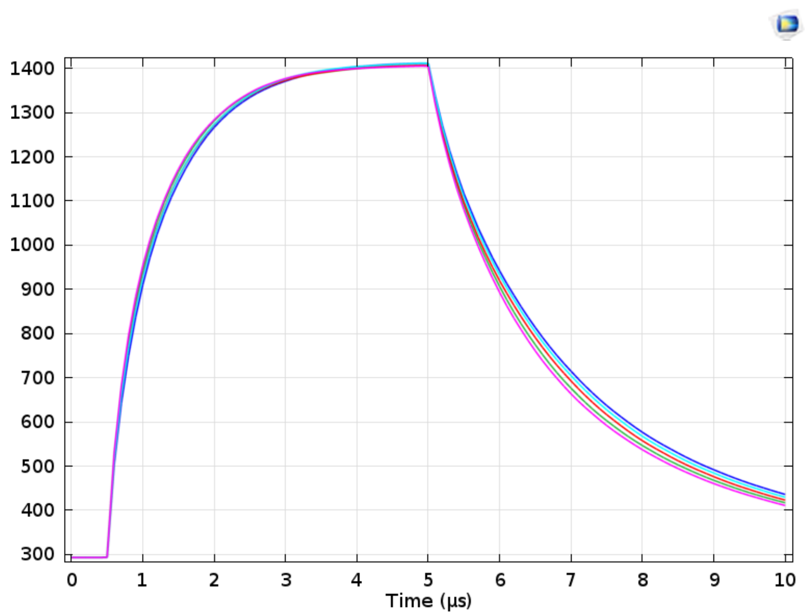

Fig. 4.6 Variation of Temperature with time for different Thermometer thickness

4.3.2 Isolation

The Figure 4.7 shows the variation of temperature(K) with time for isolation thickness of 20nm,30nm, and 50nm. From plot, one can say that the isolation's thickness has very little influence on response time. If we look at a nanosecond scale, it is obvious that 20nm design has the fastest response time. Another interesting result from this study is that with increase in thickness, the difference between the temperatures of test layer and thermometer increase significantly. It is observed that the difference is between 5°C-10°C for 50nm at maximum temperature and goes as high as 25°C for 100nm.

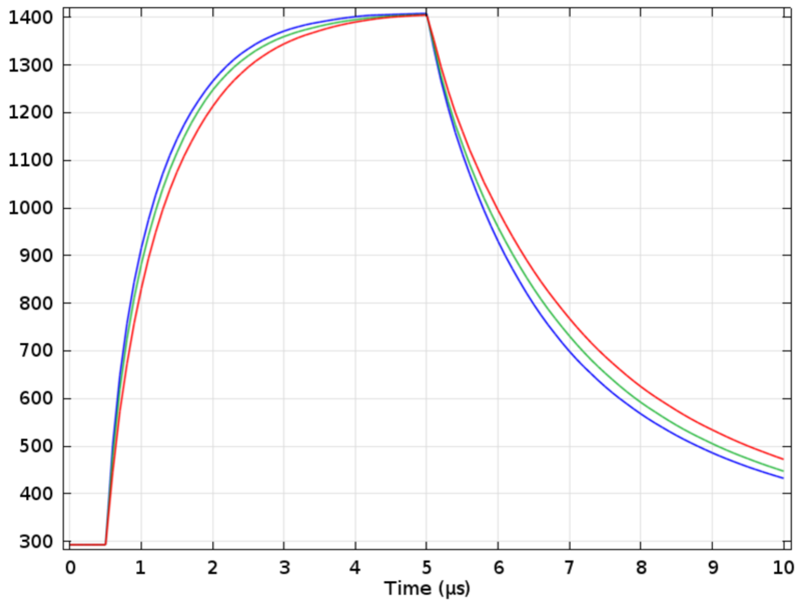

Fig. 4.7 Variation of Temperature with time for different Isolation thickness

4.3.3 Electrodes

It can be understood from previous studies that for a layer with less thickness, temperature rises more rapidly and saturates faster. The thickness in this study is increased from 20nm to 50nm and the results are presented below

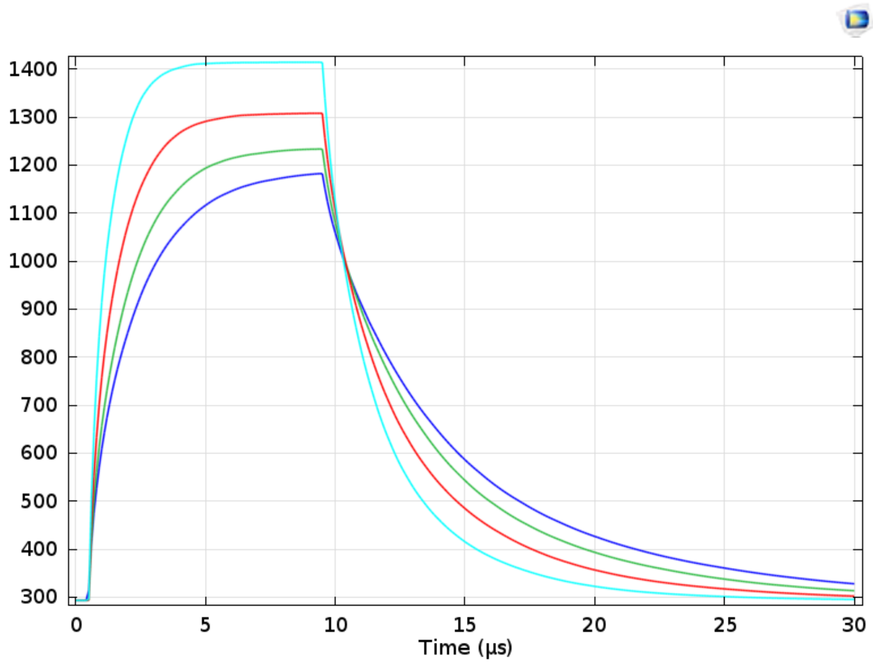

Fig. 4.8 Variation of Temperature with time for different Electrode thickness

Thickness	Response time
50nm	3.9µs
40nm	3.1µs
30nm	2.4µs
20nm	2.1µs

Table 4.2 Thickness VS Response times

4.4 Environment

The Medium in which the model is placed while measuring temperature plays an important role in determining the response time. If there is any change in the Viscosity of the medium by change in the Pressure or temperature, then there is a change in heat transfer coefficient of the model which will change the response time. The Entire study is done assuming a external natural convection but if heat transfer happens by forced convection, the response time may decrease many times.

4.5 Thermometer Pattern

The sensitivity of the measurement depends on the resistance to be calculated in the experiment. By keeping the thickness at minimum and to further optimize the resistance, a thermometer pattern as shown in figure is designed based the designs by Prajesha, R., et al. for gas sensor applications[6]. It is designed to be of double spiral structure to maintain a uniform distribution of temperature over the thermometer.

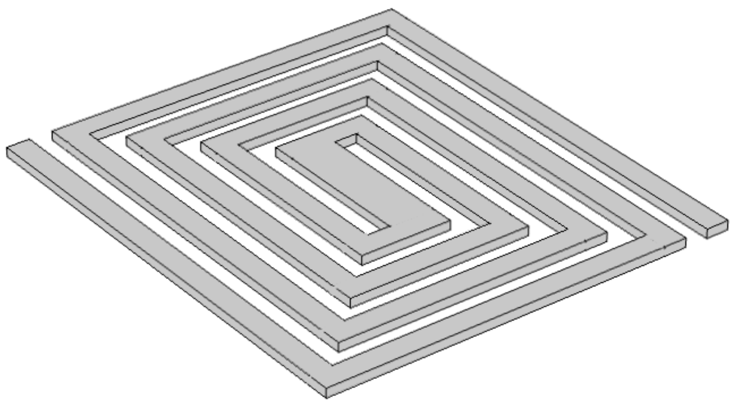

Fig. 4.9 Thermometer Pattern - Isometric View

This layer is designed to have dimensions of 2.5 µm X 2.5 µm and with thickness of varied from 10nm to 100nm. Width and gap between two beams is kept at 0.1 µm. The layer is heated by external means and a very low constant current is applied to its ends. The change in resistance as a function of temperature for different thickness is shown in the figure 4.10. It is found that the resistance is 389Ω for 50nm thickness.

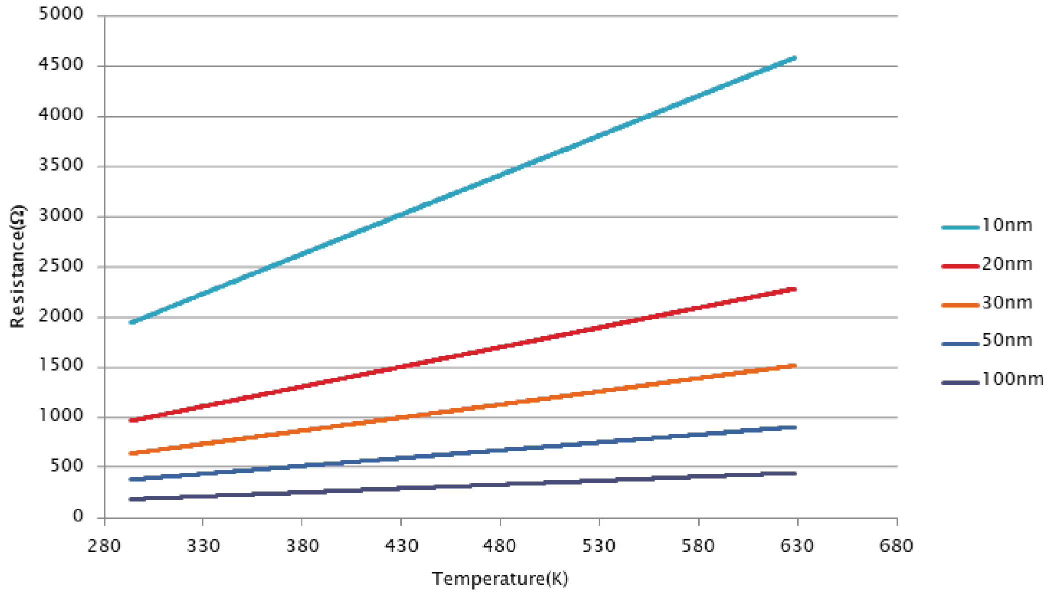

Fig. 4.10 The Variation of Resistance vs Temperature

Chapter 5

Conclusion and Future Scope

A study for suitable temperature measuring technologies was done; A COMSOL model of the design has been developed and simulations were performed accordingly.A study on different materials & thicknesses is done. Additionally, a pattern for thermometer layer was designed. Through this project, we realized the advantages, capabilities and limitations of different technologies. From our study, we come to a conclusion that thin film RTDs can be used for ultra-fast temperature measurements. Their simple structure and easy to fabricate nature makes them compatible for many other applications.

This design can now be fabricated and tested with phase change materials. For Future research, perhaps a better design with custom combination of materials can be developed and implemented which would improve the response time.

References

[hpw] Resistivity and temperature coefficient at 293k.

[2] Brites, C. D., Lima, P. P., Silva, N. J., Millán, A., Amaral, V. S., Palacio, F., and Carlos, L. D. (2012). Thermometry at the nanoscale. *Nanoscale*, 4(16):4799–4829.

[3] Brunco, D., Kittl, J., Otis, C., Goodwin, P., Thompson, M. O., and Aziz, M. (1993). Time-resolved temperature measurements during pulsed laser irradiation using thin film metal thermometers. *Review of scientific instruments*, 64(9):2615–2623.

[4] Lankhorst, M. H., Ketelaars, B. W., and Wolters, R. A. (2005). Low-cost and nanoscale non-volatile memory concept for future silicon chips. *Nature materials*, 4(4):347–352.

[5] Pinet, É. (2009). Fabry-pérot fiber-optic sensors for physical parameters measurement in challenging conditions. *Journal of sensors*, 2009.

[6] Prajesha, R., Jaina, N., Khannaa, V., Guptac, V., and Agarwala, A. (2014). Mems based integrated gas sensor for no2 and nh3. *INSTITUTE OF SMART STRUCTURES AND SYSTEMS (ISSS)*, 3(3):1–6.

[7] Wuttig, M. (2005). Phase-change materials: Towards a universal memory? *Nature materials*, 4(4):265–266.