Design and fabrication of platinum thin-film based temperature sensor

M. K. Mayuresh*, S. Harsha, S. Usha

Central Manufacturing Technology Institute, Bengaluru, India

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ABSTRACT

KEYWORDS

MEMS,
Sensors,
Temperature Sensor,
Thin-Film,
Platinum.

This article presents the development of thin-film temperature sensor with two different types of packaging techniques on silicon wafer. Platinum (Pt) thin film sensing element is designed and fabricated by MicroElectro-Mechanical Systems (MEMS) technology, based on photolithography, e-beam evaporation and lift-off techniques on silicon substrate for machine tools applications. SiO2 and Ti are used as insulation and adhesion layers respectively. The thickness of SiO2, Ti and Pt are in nanometers and coated using e-beam evaporation system. The electrical connections were established using Nickel (Ni) coated Copper (Cu) leads. Temperature sensor was extensively characterized using thermal cycling chamber and Fluke calibrator. We have observed 99.975% linearity and ± 0.5^{0}C accuracy for temperature range of -25 to 180^{0}C. The temperature coefficient of resistance (TCR) or Alpha (α) was found to be 0.002335 / ^{0}C after repetitive thermal cycling experiment. The sensor is packaged with two different techniques, epoxy packaging and stainless steel (SS) probe package. Two types of epoxies were used, one is electrically and thermally conductive and the other one is ceramic epoxy for isolation and protection. The response time of the sensor with epoxy packaging and SS packaging are 0.4 Sec and 3 Sec respectively. The response time of SS probe can be further reduced by using thin tubes.

1. Introduction

Micro-sensors technology is evolved very drastically in the last few decades. The reason behind using MEMS technology is because of it's the advantages like low power consumption, cost-effective production, small size, and weight, highly sensitive and stability makes it more suitable over conventional processes. Advance Micro-Electro-Mechanical Systems (MEMS) technology made it possible for thin-film sensors to be applied on smart devices for their extensive applications. Materials which have been generally used for thin film temperature sensors have to provide wide temperature range, accuracy, and stability such as platinum and gold.

This work focuses on the design, fabrication, and packaging of temperature sensors for industrial machine tools applications like CNCs, Polishing, Grindings, etc. in the harsh industrial environment. We have carried out the literature survey as well as research on industrial standards and requirements. This article brings out the design parameters, fabrication processes, test results, and final sensor specifications.

The demand for sensors in various industries is growing due to the full or semi-automation and the micro-sensor's capabilities to withstand in an industrial harsh environment with the support of advanced micro-packaging technologies. The machine tools and precision types of machinery are placed in a very harsh industrial environment. Vibrations, shocks, temperature variations, pressure variation, humidity and so on. These factors affect the production line and directly or indirectly results into efficiency reduction and sometimes a system failure. To reduce the negative effect of these external parameters and improve the working efficiency we need real-time health monitoring. Among those parameters, the temperature is a key parameter to monitor the system. The task like measure and maintain the particular temperature is common in all industrial, biomedical, food, defense production and operations processes. Temperature is a key parameter of machine health monitoring and high accuracy or ultra high precision production line.

*Corresponding author,
E-mail: kagalkarm@gmail.com

1.1 Types of temperature sensor

1. Resistance Temperature Detectors (RTD)
2. Thermocouples
3. Thermistor
4. Optical Temperature Sensors (IR, OFC)

RTDs are temperatures sensors in which resistance of sensing material changes with respect to temperature. Thin-film RTD based temperature sensor (as shown in Fig.1) was chosen due to a number of advantages it offers over the others. Low resistance of 100Ω (most common) to 2kΩ, high sensitivity compared with thermocouples, very accurate (±0.0006°C to 1°C), nearly linear over a wide temperature range (more than thermocouples, wide-span of operating temperatures (-200°C to 850°C), high repeatability and stability (industrial models drift < 0.1°C year-1).

These advantages and a lot of application areas make thin-film RTD the most consumed temperature sensor. There are three different types of RTDs based on design and construction.

1. Thin Films
2. Wire wound
3. Kapton Insulated

Thin-film RTD offers various advantages; fast operation/response, cost-effective bulk production and packaging. From a mechanical point of view, they are small, lightweight and very insensitive to mechanical vibrations. Due to the availability of bond pads, they can be directly integrated with electronics and do not require additional wiring. The mechanical design makes the sensor very rugged for a heavy duty thermal cycles. Due to the possibility of high base resistances, very low power measurement electronics are possible, which helps to improve measurement accuracy to lower self-heating. For temperature stabilization applications, a heater can be implemented with the same technology. If required, the sensor and heater can be combined on the same die.

1.2 Working principle

An RTD is a passive circuit element whose resistance increases with increasing temperature (Positive Temperature Coefficient) in a predictable manner. The physics behind the change in resistivity is the movements of atoms in their respective lattice. These movements or vibrations increase with the increase in temperature, which affects the mean free path (restricts electron flow) and results in an increased resistivity. For metals, the temperature coefficient is positive in nature, also known as the Positive Temperature coefficient (PTC). The traditional RTD element is made up of a small coil of platinum, copper, or nickel wire wound to a precise resistance value around a ceramic or glass bobbin. Today RTDs are also being constructed using a thin-film of platinum or nickel-iron metal deposited on a ceramic substrate and then laser-trimmed to the desired reference resistance. The advantage offered by this construction is that the thin-film elements can achieve a higher resistance with less metal, and over smaller areas. Thin film RTDs are smaller, cheaper with a better response than their conventional wire-wound counterparts.

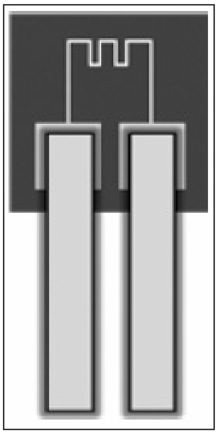

Fig. 1. Typical thin-film RTD.

1.3 Temperature Coefficient of Resistance (TCR) or Alpha (α)

The TCR or alpha value indicates the average resistance change of the sensor per °C over the range of 0°C to 100°C. The TCR or alpha value is also used as an indirect measure of the sensitivity of the resistive element used in the RTD. Its units are usually expressed in Ω/Ω/°C, or ppm/°C. Its value is derived by dividing the difference between the sensor resistance at 100°C and the sensor resistance at 0°C, by the product of sensor resistance at 0°C, and 100°C as follows:

$$TCR = \alpha = \frac{(R100^{\circ}C - R0^{\circ}C)}{R0^{\circ}C \text{ x } 100^{\circ}C} /^{\circ}C \quad (1)$$

Where, $R_{0^{\circ}C}$ is the element resistance at 0°C; and $R_{100^{\circ}C}$ is element resistance at 100°C.

2. Device Design and Fabrication

2.1 Sensing element design

The design for low and high temperature range are shown in Fig.2 and Fig.3 respectively. These sensors cover the wide range of applications from -25^{0}C to 180^{0}C. Sensing element is nothing but the passive resistive component which responds to the external temperature change in terms of change in resistance. Resistance of sensing element can be calculated as

$$R = p\,L / A \;\; \Omega \qquad (2)$$

Where, R is the resistance of the element, *p* is the resistivity of the sensing material, L is the Length of the element and A is cross section area of element. Base resistance is the resistance of sensing element at the ^{0}C or Room Temperature (RT) or specific temperature. Two designs as shown in Fig. 2 and 3 are designed with various length and width of sensing element to achieve high and low temperature ranges. In these designs, length varies from 7 mm to 15 mm and width from 10 to 15 µm. The bond pads are created for electrical connections. Bond pads are made up of same sensing material i.e. Pt to avoid contact resistance effect. Bond pad size is kept larger to attach leads manually. An existing bond pad size 500 x 1000 µm can be further reduced in case of automated machine based lead attachment technique.

2.2 Material selection

Choosing a suitable material is a major task in any kind of thin film-based sensors and actuators. The materials listed below have their own advantages and features for thin film based resistive sensing. The comparative Table 1 discusses about the resistivity, temperature coefficient of resistance (TCR), cost of material and sensing temperature range.

Platinum (Pt) offers a variety of advantages over the other materials specifically for temperature sensing applications. The various advantages offered by Platinum are good thermal response, positive temperature coefficient and highly linear,

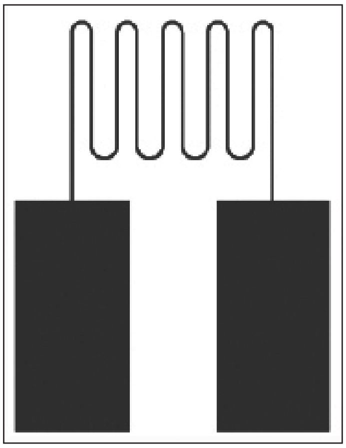

Fig. 2. For Low temperature applications (0 to 100^{0}C).

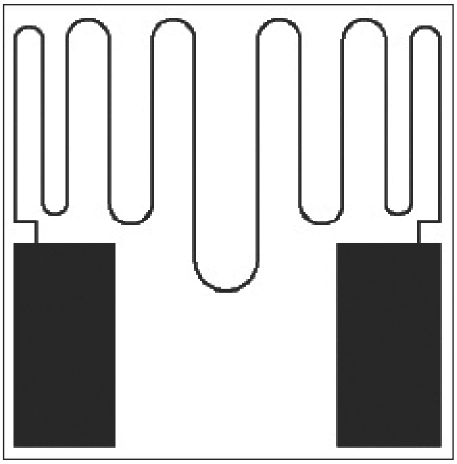

Fig. 3. For High temperature applications (-25 to 180^{0}C).

Table 1
Comparative study of materials for RTD.

Material	Resistivity (ρ) x 10^{-8} (Ω·m)	TCR (α) x 10^{-3} (ppm/°C)	Cost (INR/10gm)	Temperature Range
Al	2.82	4.29	1.4	- 40°C to 160°C
Cu	1.68	3.86	4.5	- 75°C to 150°C
Ni	6.99	6.7	8.90	- 100°C to 300°C
Pt	10.6	3.93	25480	- 200°C to 850°C
Au	2.44	4.0	31000	- 150°C to 300°C

excellent long term thermal and mechanical stability, corrosion resistant and chemical inertness, high melting point, easily purified and acts as heater as well as temperature sensor.

It is observed from Table 1, that Nickel has the highest TCR and second-highest resistivity. Although platinum seems better than Nickel, it costs much more and one has to use lift-off which is harder to control accurately to define the pattern. Thus, Nickel also can be adopted as the sensing material.

In thin-film RTD sensors, generally Pt thickness is preferred from 100nm to few microns must be strongly attached to an atomically smooth polished silicon wafer. Without an intermediate adhesion layer between the Si and Pt, the attachment is weak and fails to withstand annealing temperature stresses of 600°C or more. Annealing is required to give stable electrical characteristics to Pt. Metal adhesion layers are not satisfactory because, although some metals adhere satisfactorily to both the nitride and the platinum, all suitable refractory metals that have been investigated (including chromium, titanium, tungsten, nickel, iron, and tantalum) diffuse into the platinum during the annealing process. This adversely change its electrical characteristics by increasing its resistivity and reducing its temperature coefficient. But still metallic adhesion layers are used to improve the adhesion with Si. Typically, Titanium (Ti), Tantalum (Ta), and Chromium (Cr) are commonly used.

Titanium is used mostly as an adhesive layer for Pt RTDs, it offers good adhesion with Si/SiO$_2$, Glass substrate and Platinum, very low resistivity, increases resistivity of Pt after annealing due to diffusion. By keeping these points in mind we have selected Ti as an adhesion layer for our sensor.

2.3 Fabrication

The Fig. 4 shows the fabrication process flow of the sensor.

The fabrication process starts with the preparation of the Silicon (Si) wafer. We have developed the fabrication process for a 4-inch sized Si wafer. Wafer was cleaned by DI water, Acetone, IPA and Methanol to clean the organic, inorganic and metallic contaminations. The wafer was later thermally oxidized for the SiO2 coating as an insulation layer. SiO2 of 100nm was coated on Si wafer via thermal oxidation. In the Fig. 4, SiO2 is indicated in green color. Spin coating of photoresist was done and then mask design was transferred using LASER direct writing. The red color is used for Photoresist in the figure 4. After the development process, the wafer was taken to e-beam evaporation process. Pt and Ti were available in the pellets form and loaded to the e-beam evaporation system (EBS) crucibles. Thin layer Ti (20nm) and Pt (230nm) were uniformly coated using EBS. Orange color indicates the Ti/Pt layer. Lift off of unwanted Ti/Pt layer was done in wet-bench using Acetone bath and Ultrasonicator. To regain the structure or to avoid the structural/growth defects in thin films annealing is recommended. Annealing of lifted off wafer was done at 500^{o}C for 1 hour. Characterization (metrology) was done at all intermediated stages for verification of desired design parameters.

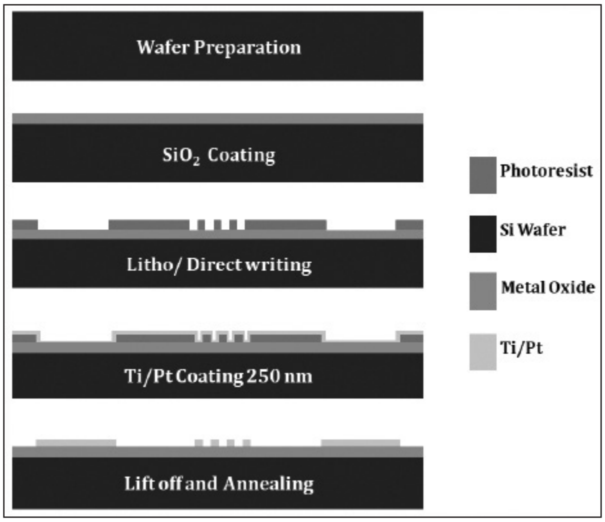

Fig. 4. Sensor fabrication process flow.

Fig. 5 and Fig. 6 show the microscopic images of fabricated devices.

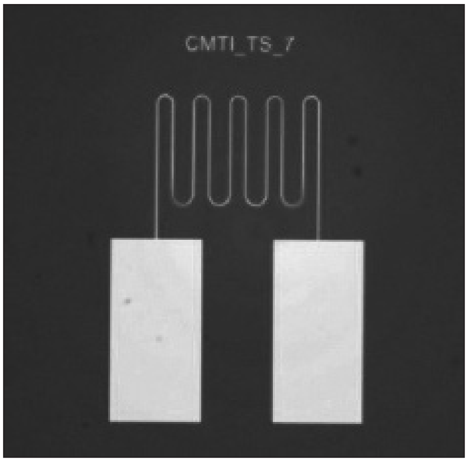

Fig. 5. Microscopic image of fabricated device for 0 to 100^{0}C.

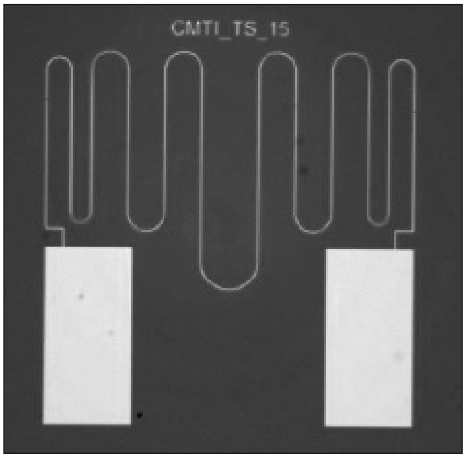

Fig. 6. Microscopic image of fabricated device for -25 to 180^0C.

3. Packaging

Packaging plays a vital role in sensor performance as well as protection from the external environment. The temperature sensor will be used in a harsh industrial environment, dust, oil, pressure variations, human interaction etc. Packaging involves wafer dicing, die selection and attachment, wire/lead bonding, encapsulation, plating, sealing or welding, etc. In addition to protecting the delicate RTD element, the sheath or surrounding medium of the RTD element must maximize the heat transfer from the sensed material to the element, but also minimize the heat transfer from the ambient to the element itself. The proper choice of packaging material in construction becomes very important to ensure the accuracy of your reading for a given application. Likewise, application considerations like the immersion depth of a probe are important.

3.1 Wafer level testing and die selection

Once the wafer-level fabrication of sensors was completed, characterization was carried out for the selection of working devices. For temperature sensor, typically, resistance will be measure using a Wafer Probe Station. It is a four-probe measurement technique used for I-V characteristics of devices.

The four-point probe station is used to inspect the sensor resistance at room temperature. At wafer-level testing, it is observed that resistance of sensors is in decreasing order towards wafer edges from the center. To ensure the behavior data is verified with the Pt thickness distribution. Ideally, thickness throughout the wafer should be uniform but due to practical constraints/tool limitations, it will exhibit non-uniformity. This may result in a sensor to sensor performance variation.

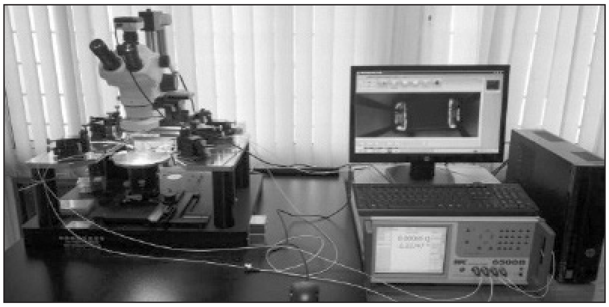

Fig. 7. Four-point probe station with impedance analyzer at CMTI.

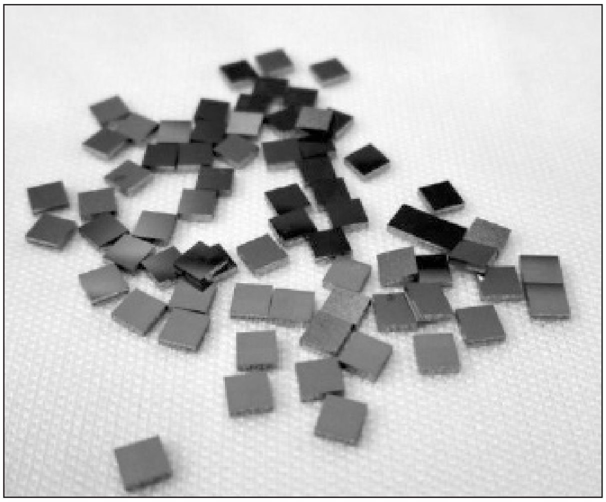

Fig. 8. Diced working devices.

After the wafer level testing, wafer diced to single devices using in house wafer dicing facility. Fig. 8 shows the diced devices from the 4 inch Si wafer. The diced final device size is 2.5 mm x 2.5 mm.

Based on a visual inspection and resistance measurement working dies were selected and sorted out based on design and application.

3.2 Lead attachment

To establish electrical connection leads were connected to bond pads. Usages of dissimilar metal leads will lead to the contact resistance problem. So avoid contact resistance issues using similar resistivity metal leads which are recommended. Considering this point we have decided to go ahead with Copper (Cu) leads which have very good conductivity and coated with Nickel (Ni) which has resistivity closer to Pt. Although Pt lead is an ideal solution, it is very expensive.

The following Fig. 9 shows the Ni electroplated lead attached to bond pads using electrically and thermally conductive epoxy. For low temperature applications Epotek H74 and for high temperature application Tedpella make HiRel Silver paste is used.

3.3 Device enclosure

3.3.1 Epoxy package

To protect the device from the external environment and improve the adhesion of leads to the bonds, electrically insulating and thermally conductive epoxy was applied to the final device. For low temperature applications Epotek H70E and for high temperature application Tedpella make HiRel Ceramic paste is used.

Fig. 10 and 11 show the epoxy packaging of the final device. Fig. 10 shows the wet epoxy applied to device and kept on hot plate for curing and Fig. 11 shows the fully cured epoxy sensor. These types of packaged sensor can be used in surface-mount based applications. Most of the machine tools require the sensors to be placed on the surface of stages, tools, beds, motors where the area is very limited. In specific cases, sensors to be placed inside the rigid body parts by drilling into it. In such applications epoxy packaged sensor is helpful.

3.3.2 Stainless Steel (SS) probe package

An epoxy packaged sensor has limitations of using directly into the gas or liquid media for temperature measurement application. Conducting fluids may short circuit the sensor signal, damage the leads (oxidation), damage or react with Si substrate. So to avoid further damages, SS probe packages are used. A hollow SS tube is used to package the epoxy enclosed sensor, where on end of the tube is sealed using in house electron beam welding facility.

But the sensor cannot be put directly inside the tube and sealed because of the thermal conductivity issue. The air gap between the probe wall and sensor acts as thermal insulation where the sensor may not be able to measure. So pack the sensor with proper thermal conductive material which should be electrically insulating as well, we have filled SS tube with MgO powder to ensure there are no voids between probe wall and sensor. The main reason for MgO is as mentioned earlier it is a very good electrical insulator at the same time it has thermal conductivity of 30-40 W/mK where SS has 15-20 W/mK. Following X-ray scanned images (Fig. 12 and Fig. 13) show the SS probe package. Fig. 12 shows the e-beam sealing of tube end.

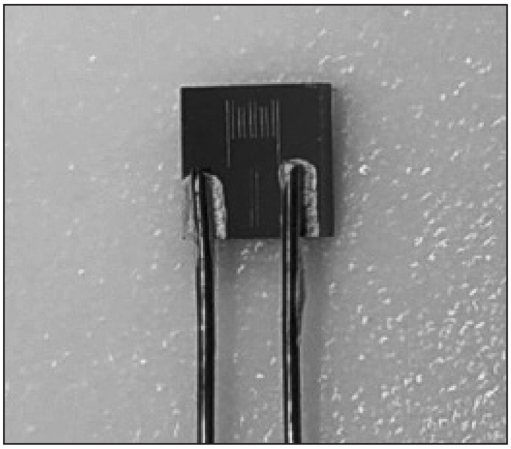

Fig. 9. Ni coated Cu Lead attachment.

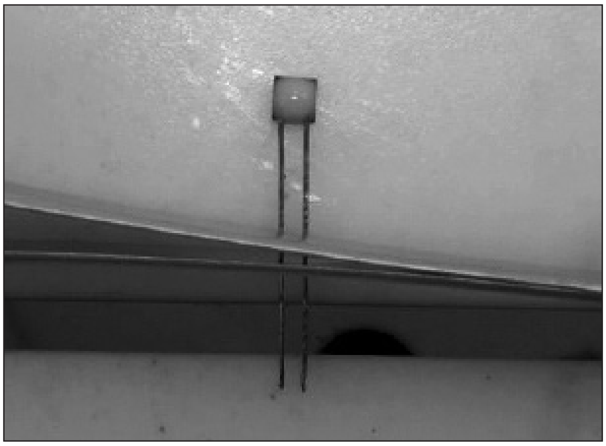

Fig. 10. Epoxy enclose on lead attached device.

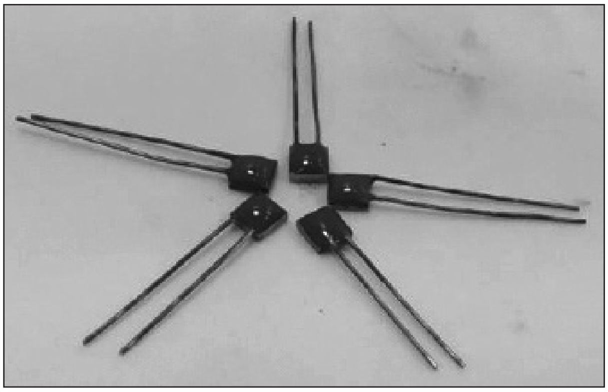

Fig. 11. Curing of epoxy.

The other end of the SS probe is sealed with epoxy and covered with shrinkable rubber sleeves, which can be seen in Fig. 13 black in color.

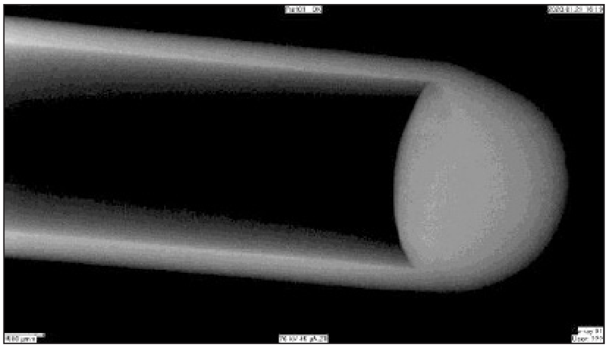

Fig. 12. SS probe one end e-beam sealed.

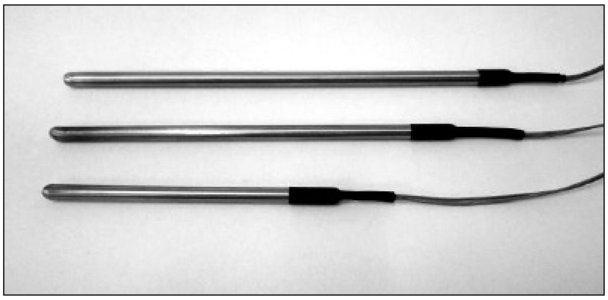

Fig. 13. SS probe packaged final devices.

4. Results

The sensor performance test was carried out using in house thermal cycling chamber facility. The sensor performance is evaluated based on various parameters. Sensitivity, Linearity, Accuracy, Response Time, Repeatability and Stability are measured using standard measurement techniques. Temperature Coefficient of Resistance (TCR) or Alpha (α) is calculated after repeated thermal cycling experiments. TCR can be calculated using equation (1). Resistance at 0^0C and 100^0C were measured and TCR was calculated. The calculated TCR is $\alpha = 0.002335\ /^0C$. The slope of the graph is nothing but the sensitivity of the sensor. The sensitivity of CMTI RTD, $s = 2.485\ \Omega/^0C$ and Accuracy observed is $\underline{+}0.5^0$C.

Linearity was found from the graph (Fig. 14) shown below 99.975%. Sensor exposed to the full working range from -25^0C to 180^0C and resistance was recorded in 20^0C interval.

For Stability, the sensor was exposed to the same temperature (80^0C) for 5 hours duration for consecutive 5 days. The results conclude that the sensor deviated by 0.2^0C as shown in Fig. 15.

Repeatability was tested for continuous 5 days for temperature range of 0 to 150^0C. Following graph (Fig. 16) shows the 5 days temperature data plotted against resistance.

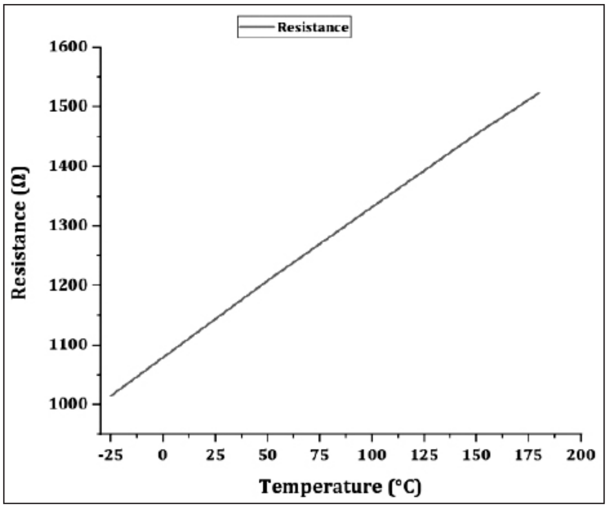

Fig. 14. Graph resistance response to temperature.

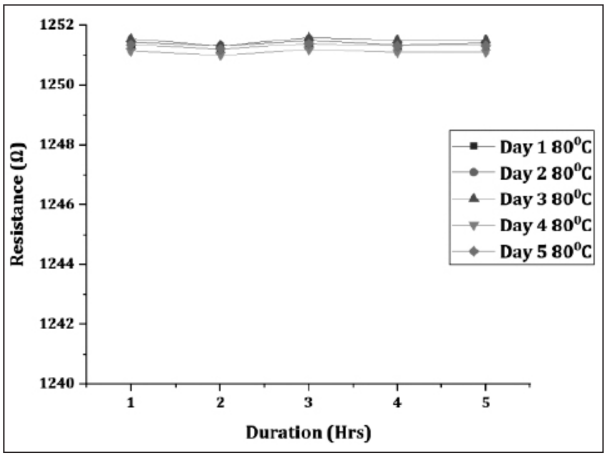

Fig. 15. Graph resistance response to constant temperature for longer duration.

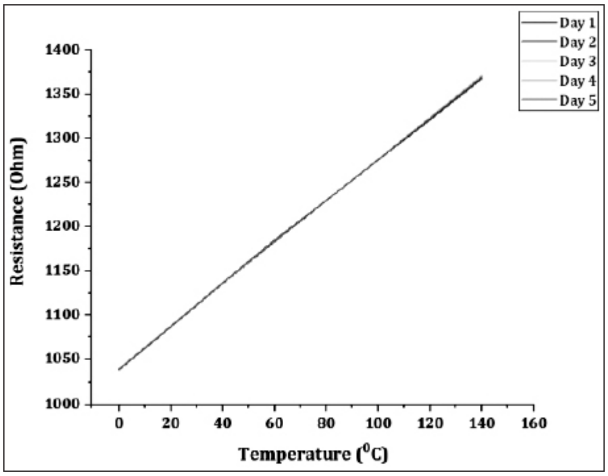

Fig. 16. Graph resistance response to repeated temperature cycling.

Graph (Fig. 16) shows that all 5 days data coincides in other words sensor gives same response for multiple recurrences. Response time: The Ice bath set-up was prepared for the response

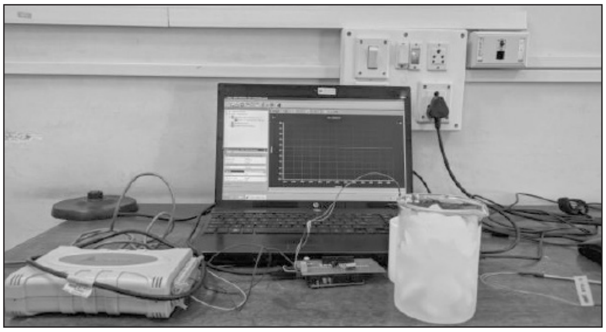

Fig. 17. Ice bath test setup for response time measurement.

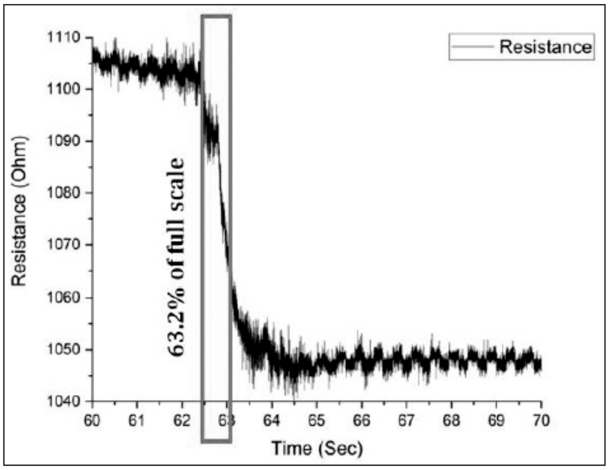

Fig. 18. Response time of epoxy packaged sensor.

time testing as shown in Fig. 17. The response of sensor to the sudden change of temperature from room temperature (RT) to 0^0C was recorded using data acquisition module. Sensor was kept in beaker-1 which has water at RT (26^0C) and data acquisition was initialized with 1000 samples per sec rate.

After completion of one minute the sensor was suddenly immersed into the ice bath which is at 0^0C. Later data was taken to PC and graph was plotted for Resistance vs Time. The Fig. 17 shows the sensor response when sensor was immersed into ice bath and large resistance drop is observed. The 63.2% of full scale (RT to 0^0C) is considered as response time of sensor. Response time was recorded, t = 0.4 sec. The Fig. 18 shows the graph plotted resistance vs Time.

Same way the SS probe packaged sensor response was recorded and it was found to be 3 sec. Probe packaged sensors are not used where very low response time is required, like fuel based systems. But major contribution to the response time is done by tube material and its wall thickness. Thinner and high strength tube can solve the high response time issue.

5. Summary

The motive behind this work is to develop a thin film based Pt temperature sensor for machine tools applications. The major area of application is cutting tools and oil baths temperature measurement. CMTI sensor team took challenge to develop sensor using in house facility with the support of IISc, Bengaluru. The sensor was designed with two temperature ranges, 0 to 100^0C and -25 to 180^0C. The masks designs were prepared using DraftSight and CleWin software. Using Laser writing facility at CMTI, lithography was done. Later wafer was processed under e-beam evaporation system for Ti/Pt thin film deposition. Lift-off was carried out to remove the unwanted Ti/Pt layer. Further the wafer was annealed to recover molecular structures of Ti and Pt from growth and stress defects. Dicing was done after annealing and good devices were sorted out. Then Ni electroplated Cu leads were attached to the final devices for the electrical connections. The leads were attached using conducting epoxy and were enclosed with non conducting epoxy for environmental protection. Sensors were further packaged in SS probe tubes with MgO powder. Extensive testing of sensor was done to characterize and evaluate performance. The linearity was found to be 99.975%, Accuracy of $\underline{+}0.5^0$C and sensitivity $s = 2.485\ \Omega/^0$C. The response time was measured using ice bath and it was found to be 0.4 sec and 3 sec for epoxy packaged and SS probe sensor respectively.

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Mayuresh Kagalkar holds a master's degree in Sensor systems from VIT University, Vellore. He is currently working as a Senior Research Fellow, Centre for Sensors, Vision Technology and Controls (C-SVTC), Central Manufacturing Technology Institute (CMTI), Bengaluru. His areas of expertise and interests are Micro-Nano systems, MEMS/NEMS, and polymer-based device development and related application development. He is responsible for the design and development of micro-nano sensors and actuators at CMTI. Currently he is working on productizing of thin-film-based temperature sensors and an array of sensors for industrial and defense applications. Mr. Mayuresh is developing high speed and high-resolution data acquisition setup and algorithm for the sensor array. He is also supporting ongoing device development and R&D activities for ventilators within the department. He has successfully designed a cleanroom layout for new laboratory building and also played a major role in setting-up stand by cleanroom and microsystems packaging facility at the Sensor Technology Development Centre (STDC), CMTI. He has presented 4 research papers in national and international conferences and has been awarded "Best Paper Award" for 2 research papers in the year 2015 and 2020.

Harsha S. is currently working as a Scientist in Centre for Sensors, Vision Technology and Controls at Central Manufacturing Technology Institute, Bengaluru. He is a post graduate in VLSI design and embedded systems, and is a Bachelor of Engineering in Electronics and Communications. He is mainly involved in micro systems packaging processes viz., wafer dicing, wire bonding, bond testing, flip chip bonding and thin film deposition.

S. Usha is a Graduate in Electrical & Electronics Engineering from Thiagarajar College of Engineering, Madurai with M.Tech (Research) in Mechatronics from NITK, Surathkal. She was responsible for providing automation solutions using machine vision technology and sensor development at CMTI. Superannuated from CMTI in April 2020. Her 36 years of experience at CMTI mainly focused on mechatronics related product development including the development of Control Instrumentation, PLC, Machine Interfacing & Testing, Robotics & Machine Vision, PC Based Automation Controller, Virtual Instrumentation, SCADA development, and MEMS-based sensor development. Her significant contributions at CMTI include: Development of Automated Test Facilities (Performance, Endurance, and Impulse) and Virtual Instrumentation using LABVIEW / LABWINDOWS & Data Acquisitions Systems for Hydraulic elements like Actuators, Servo valves, etc. Development Algorithms for Part Identification and Interface to SCARA Robot for Pick and Place assembly operation. Design and development of Multi Gauging Automated Inspection System for complex components for the strategic sector. Control System design development for special purpose machines with remote control and monitoring through PLC & SCADA. Involved in the development of various vision-based inspection systems (2D and 3D). Published more than 18 research papers in national/international conferences. Received Patent for development of 'Adaptive Controller' in the year 1991 and another for "Method and System for Thermal Error Compensation in Machines by Vision Measurement'' published in 2014.