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NOTE

Metal substrate printed circuit boards as low-cost, robust temperature sensor mounts for cryogenic thermometry

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Abstract

Cryogenic experiments strongly depend on accurate temperature measurements. Many of the sensors used for these purposes are glued to the object to be measured to achieve adequate thermal contact. This calls for a more flexible, long lasting and robust bolt-mounted solution. Therefore, we present a low-cost (<5$), compact, PCB (printed circuit board) based sensor mount for RTDs (resistance temperature detector) and diodes showing reliable results at temperatures from 50 K to 400 K with possible modifications for an extended range down below 20 K. We anticipate that the robustness and low cost of the reported sensor mount design will strongly enhance the accessibility of reliable temperature measurements at a wide range of temperatures in laboratory applications.

1. Introduction

Accurate temperature readings are of utmost importance in many laboratories. A temperature sensor usually consists of a resistance temperature detector (RTD), a diode, or a thermocouple. An RTD can have either a positive (PTC) or a negative temperature coefficient (NTC). For both temperature measurements in the cryogenic regime and above 300 K, a platinum sensor is widely regarded as a sensible choice [1, 2]. Platinum sensors are often marketed as Pt100, Pt500, or Pt1000, where the number corresponds to the resistance value in Ohms at 0 °C. Platinum has a positive temperature coefficient, and thus, excitation with a constant current is the most appropriate measurement setup to read the temperature. Similarly, a constant current can be applied to a silicon diode, and the temperature-dependent forward voltage can be read. A thermocouple relies on the temperature-dependent thermoelectric effect of the junction of two materials. To achieve an accurate measurement, the cables connecting the thermocouple to the readout device must be made of the same materials, which requires special feed-throughs when used in a vacuum chamber. We focus on RTDs and diodes as temperature sensors in this paper.

RTDs are relatively inexpensive and readily available from various manufacturers but are mostly produced in fragile packages with thin wires to reduce thermal flow from the connected cables. They must be glued to the object which needs to be measured. This can provide good thermal contact, but it is not guaranteed to be reproducible. The process is irreversible, as the sensors will likely break upon removal. Special diodes rated for use as cryogenic temperature sensors can be purchased in different packages from manufacturers such as Lake Shore Cryotronics, Inc. [3]. They provide excellent thermal contact but are expensive and fragile as they are equipped with very thin leads as well. Lake Shore Cryotronics, Inc. also offers bolt-down Platinum temperature sensors in a similar price range.

Printed circuit boards (PCBs) are commonly used to connect electrical components with a good electrical, thermal, and structural bond. Circuit boards used in commercial applications usually use FR-4, a glass-reinforced epoxy laminate material, as a substrate since this is highly flame-resistant and an insulator [4]. For applications requiring good heat dissipation, other base substrates such as aluminum [5] can be used. This option is readily available among manufacturers. Alternatively, copper substrate offers better heat dissipation but is more expensive and manufacturers currently only offer it in large quantities. Temperature sensors, such as diodes or platinum RTDs, also exist in surface mount device packages (SMD), which can be easily and reliably soldered onto a PCB. This suggests a simple assembly for compact temperature sensor mounts.

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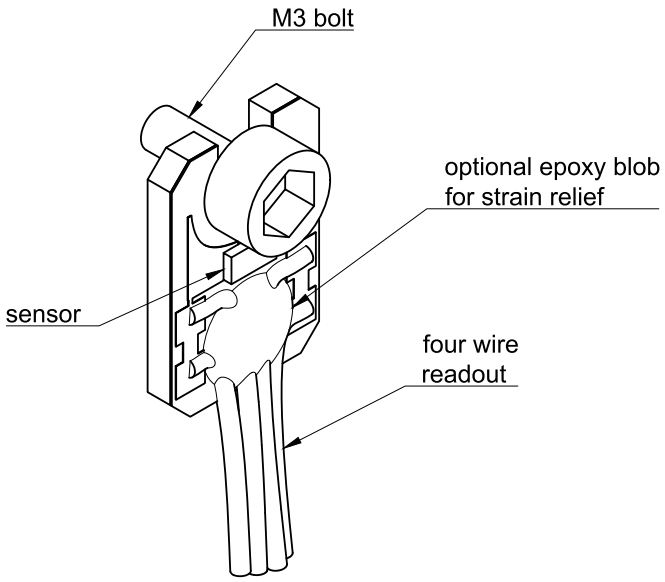


Figure 1. General overview of the sensor mount with robust AWG24 wires attached and a bolt in place.

We present a relatively inexpensive bolt-down sensor mount that promises good thermal contact, flexibility and robustness. A representation of the assembled sensor mount is shown in figure 1.

2. Method

The sensor mount consists of a PCB with aluminum substrate material. The sensor was designed to be of similar size as the DT-670 BO package from Lake Shore Cryotronics, Inc. [3], due to the constraint of placing solder pads and traces, our sensor mount is wider but thinner, see figure 2. The specifications are listed in table 1. A copper thickness of 0.035mm (corresponding to 1 oz copper weight) and an insulation layer composed of aluminum hydroxide and silica with a thickness of 0.1 mm and a thermal conductivity of 1 W / m K at room temperature have been selected [6]. No solder mask was applied to prevent out-gassing and, therefore, make it ultra-high-vacuum (UHV) compatible. The thermal conductance in equation (1) is given by the ratio of heat flow $\dot{Q}(T)$ and temperature difference, ΔT. It can be derived from the definition of the thermal conductivity, $\kappa(T)$, and thus also depends on thickness, d, and area, A.

$$K(T) = \dot{Q}(T)/\Delta T = \kappa(T)/d \cdot A \tag{1}$$

This design aims to guide the thermal flow from the cables directly onto the sample and away from the sensor. Therefore, the thermal flow and, correspondingly, the thermal gradient between the sensor and the sample is minimized, which in turn decreases the systematic error of the measured temperature. This is a key goal in the design of this sensor mount. To reduce the thermal flow through the thermal paths connecting the solder pads of the wires and the sensor, the traces need to have a maximum length, d, and a minimum cross-section area, A, as seen in equation (1). The paths connecting the solder pads of the wires to the sink object (sample) need to have maximum cross-sectional area, A, with the thickness, d, set by the thickness of the insulation layer of the PCB. To provide an alternative to the fragile connections of commercial sensors, durable AWG24 wires will be soldered directly to the pads and can, for extra robustness, be epoxied to the sensor mount to provide better strain relief. We focus our work on a robust design that works reliably in thermal equilibrium. We do not characterize the sensor mount's dynamic properties.

Since the temperature-dependent thermal properties of copper, aluminum and epoxy are well documented [7, 8], we performed steady-state simulations with Ansys Mechanical [9] for AWG24 copper wires with length of 100mm. The temperature gradient is shown in figure 3. From the simulation, we can see that about 1 W flows through the cables (assuming that the sample is at 23.15 K and the cables are connected to an object at 300 K). Only about 5% flows into the sensor, the rest is directed onto the sample. The simulation has been run for different sample temperatures, which shows the systematic offset we can expect on the sensor as shown in figure 4. This simulation shows that while our design is as compact as connecting the wires directly to a sensor without additional external thermal grounding, it still provides excellent results down to $T = 50$ K, with a slight systematic error around $T = 20$ K.

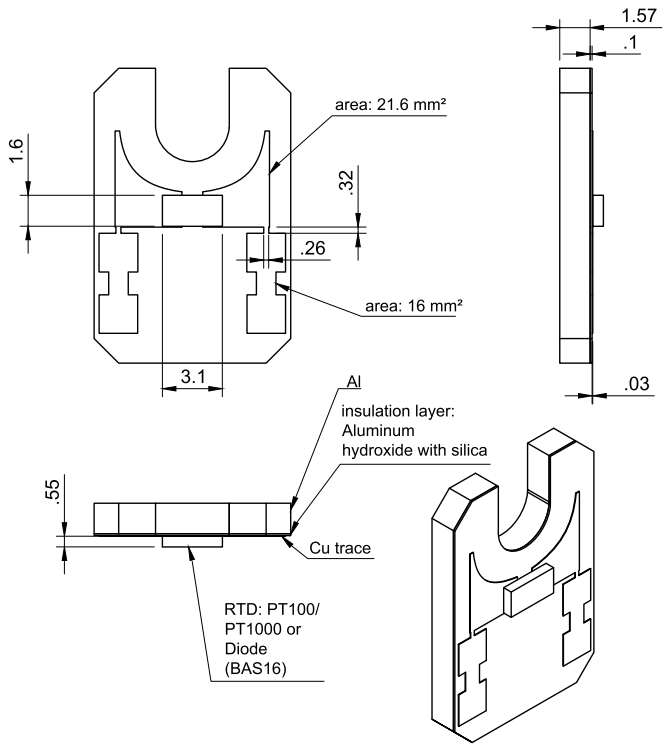


Figure 2. Drawing of the sensor mount PCB showing the dimensions of the traces and layer thickness. Units are given in [mm].

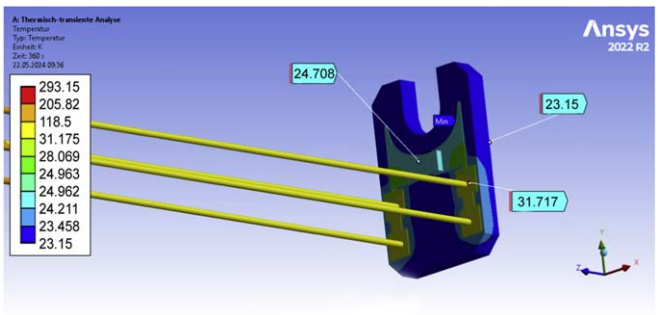


Figure 3. A Thermal simulation run with Ansys Mechanical. The sensor is connected to a sink object (sample) with fixed temperature of 23.15 K. Four simplified AWG24 wires with length of 100 mm are connected to the solder pads and the other end is at a fixed temperature of 300 K. To simplify the simulation, radiation has not been considered.

The radiation onto the sensor, with the assumptions given in table 2, is given in equation (2) by the black body radiation [10], assuming that the sensor is a true black body to obtain an upper limit.

$$P_{\text{rad}} = \sigma\ A_{\text{rad}} \cdot (T_{\text{amb}}^4 - T_{\text{sensor}}^4) = 2.2\ \text{mW}. \tag{2}$$

By dividing the radiative power input by the minimum thermal conductance $K = 0.04$ W/K of the sensor mount (at 20 K), we measured in figure 6, we can estimate an induced temperature change in equation (3)

$$\Delta T_{\text{rad}} = \frac{P_{\text{rad}}}{K} = 0.055\text{K}. \tag{3}$$

This provides an upper limit to the temperature increase on the sensor, assuming an ideal black body.

3. Results

For the characterisation of the thermal properties at different temperatures, we used a Pt1000 in a 1206 SMD package from Vishay [11]. Two sensor mounts were attached to a copper adapter, which was connected to a

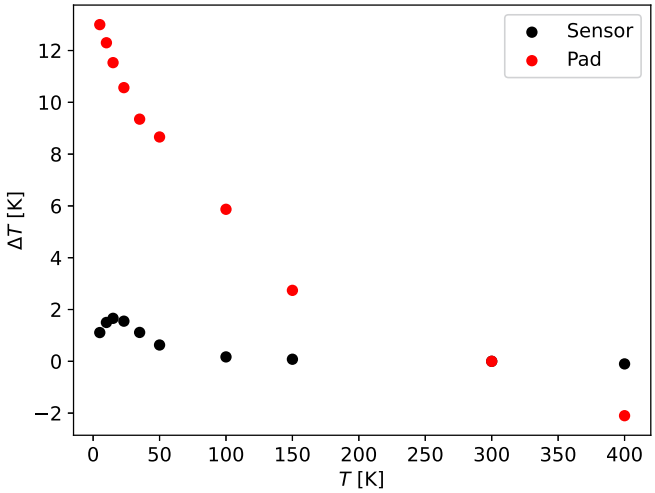


Figure 4. Simulations run for multiple object temperatures with the temperature offset of the cable pads and the sensor. Four AWG24 copper wires with a length of 100 mm and connected to ambient temperature of 300 K were simulated. The large increase in the offset of the sensor at around $T = 20$ K is mainly caused by the increased thermal conductivity of copper at these temperatures [7].

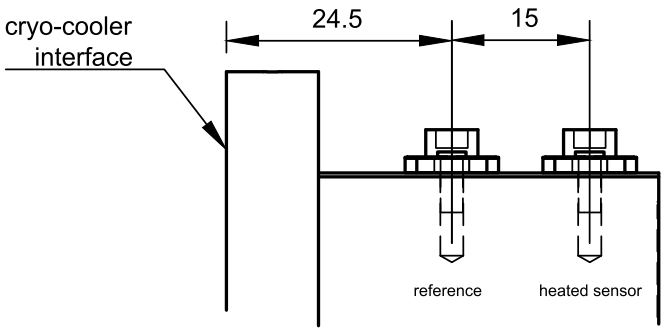


Figure 5. Side-view of the setup with two sensors screwed down on a copper adapter which is attached to a cryo-cooler. During the measurements the cryo-cooler was turned off, such that the copper block can be assumed to be in thermal equilibrium with no temperature gradient across. Units are given in mm.

Table 1. Specifications of the sensor mount, including the sensor, but without cables.

Width	Length	Height	Mass
10.16 mm	15.24 mm	2.12 mm	1.8 g

Table 2. Parameters to calculate the black body radiation of the environment onto the sensor.

A_{rad}	T_{amb}	T_{sensor}
5 mm^2	298 K	23.15 K

cryo-cooler in a vacuum chamber as depicted in figure 5. The vacuum pressures ranged from 10^{-6} mbar to 10^{-5} mbar throughout the tests. One sensor is actively and continuously heated by using a high excitation current (7.5 mA), while the other measures the reference temperature of the copper body with a standard short current pulses (0.1 mA). The high excitation current will result in a temperature difference $\Delta T = T_{excited} - T_{ref}$ which can then be used to determine the thermal conductance K using equation (4).

$$K = P/\Delta T = R\ I^2/\Delta T \tag{4}$$

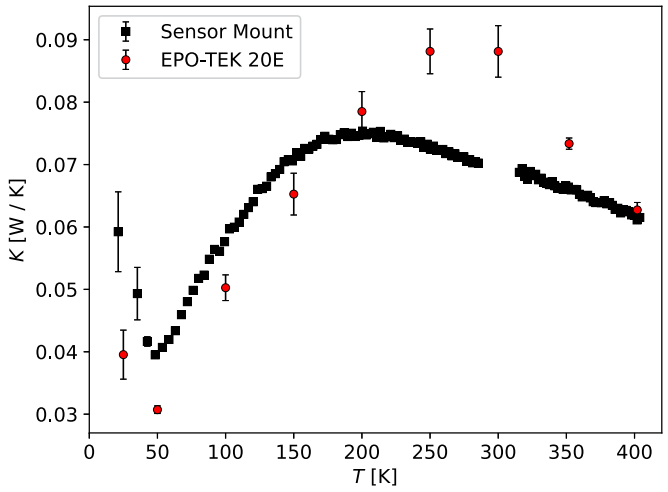


Figure 6. Thermal contact of a Pt1000 on our sensor mount compared to an epoxied Pt1000 with EPO-TEK H20E. It is important to note that we observe the net thermal conductance which is composed of all different materials (Pt, Cu, Insulator, Al_2O_3) and not the characteristic curve of one single material. The measurements were averaged over four runs.

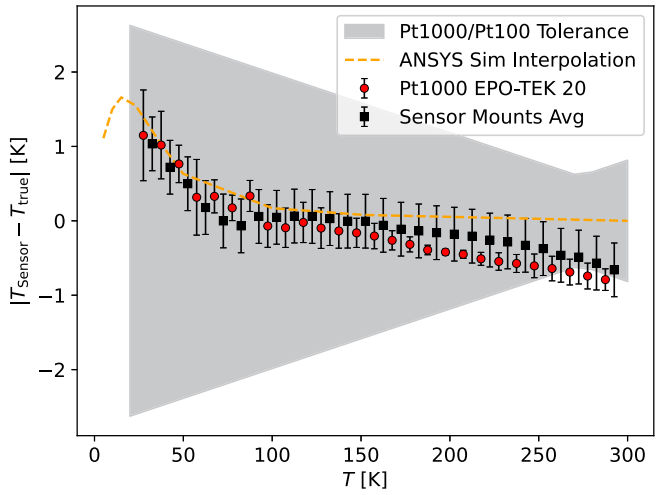


Figure 7. The Difference of the measured temperature to that of the reference Lake Shore Cryotronics, Inc. DT-670 silicon diode. The Average was taken for four Pt1000 and Pt100 sensors and two thermal cycles each. The result show reproducible and comparable results to a Pt1000 epoxied with EPO-TEK 20 and the cables taped down with aluminum tape for thermal grounding. The thermal grounding with aluminum tape was not required for our sensor mounts. Durable AWG24 wires were used. The simulation discussed in the previous section agrees with the measurements taken.

This allows us to characterize the thermal contact between the reference sink copper body and the temperature sensor attached to the sensor mount. A Keithley Model 2450 [12] was used to supply the heating current and read the resistance of the heated RTD. A Keithley DMM7510 [13] read out the reference temperature sensor.

We compared the measurement of our sensor mount with a Pt1000 (standard two-lead wire package) epoxied to a copper block with silver epoxy EPO-TEK H20E [14]. The sensor mount with the high excitation current was replaced with the epoxied Pt1000. The results taken at different temperatures are presented in figure 6 and show that our sensor mount has comparable thermal conductance K as the Pt1000 glued with silver epoxy.

Further measurements have been conducted to compare the measured temperature of Pt1000, Pt100 and BAS16 temperature sensors and the measured temperature of a reference Lake Shore Cryotronics, Inc. DT-670 silicon diode [3]. A Pt1000 epoxied to the sensor block is also included. The results shown in figure 7 confirm the temperature offset obtained from the simulations in figure 4 and show reproducible measurements across different sensor mounts with different sensors mounted on.

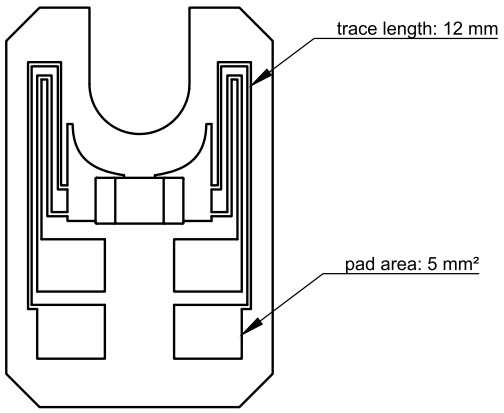


Figure 8. An adapted design with longer signal traces to decrease further the amount of heat flowing from the wire-pads to the sensor. The four-wire readout is extended up to the pads where the sensor is mounted.

4. Conclusion

We have shown the feasibility of aluminum substrate PCBs as low-cost, robust temperature sensor mounts for cryogenic temperatures. The presented sensor mount shows comparable thermal conductance (as shown in figure 6) to an epoxied RTD sensor, but with the advantage of flexible bolt-down mounting, more robustness and being more compact as there is no need for thermal grounding of the incoming wires. Durable AWG24 stranded wires can be used, which are more durable than the solid wires attached to commercial sensor packages. The measured temperatures lie within the tolerance bands of the RTD sensors with a slight systematic error of 1-2 K around temperatures of 20 K as shown in figure 7.

This sensor mount has been tested with SMD 1206 Pt100, SMD 1206 Pt1000 [11] and SMD SOD123 BAS16 silicon diodes [15] and the temperature measurements remain in the specified tolerance bands.

While commercial sensors along with the attached cables can also be epoxied to an object, this is less compact and only serves as a permanent solution, as the sensor is likely to be damaged upon removal.

We thus conclude that the thermal conductance of our sample holder design is sufficient for temperatures in the range of 50 K up to 400 K. The requirements of robustness, mounting flexibility and low cost have been fulfilled. This poses an excellent, low-cost and longer lasting alternative to expensive, fragile commercial products for applications in thermal equilibrium. Concerning reaction time, the sensor mount cannot compete with the much more expensive Lake Shore Cryotronics, Inc. diode, where the silicon wafer has improved thermal contact with the base, allowing for increased responsiveness in dynamic applications.

5. Outlook

The incoming heat from the wires to the sensor can further be decreased by increasing the length of the connected signal trace between the cable pads and the sensor pads. A possible future iteration is illustrated in figure 8. The improved design would decrease the systematic error at temperatures around 20 K.

Acknowledgments

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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