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ANALYSIS OF SEMICONDUCTOR COMPONENTS AS TEMPERATURE SENSORS FOR CRYOGENIC INVESTIGATION OF SRF MATERIALS

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Abstract

Temperature mapping systems have been used for many years to detect local heating in an SRF cavity surface or materials sample. They require a large number of temperature sensors. Most often, low-cost Allen-Bradley resistors are used for this purpose. Since they have poor sensitivity and reproducibility above 4 K, sensor alternatives that combine the precision of Cernox[1] sensors with the low-cost of Allen-Bradley resistors would be highly desirable. In this work various semiconductor components that exhibit a temperature dependent electrical response, such as diodes and LEDs were analyzed with respect to sensitivity, reproducibility and response speed in a temperature range between 6.5 K and 22 K. In this range, many diodes and LEDs were found to be more sensitive than Cernox sensors. However, in some components the response time was slow – possibly due to poor thermal contact.

INTRODUCTION

Since many years, temperature mapping systems have been valuable tools for SRF cavity R&D, for example, to detect local heating in the surface of cavities [1].

As most niobium cavities are operated at 1.8 K to 2 K a large number of high-precision temperature sensors optimized for this temperature range is needed. If the temperature is only measured at a few points, commercial Cernox sensors can be used, offering great accuracy. For large T mapping systems, mainly 100 Allen-Bradley carbon resistors are used since their low-cost allows for affordable scaling of the mapping systems.

Although Allen-Bradley resistors are applicable for temperatures below 4 K their sensitivity drops for temperatures above 4 K [2]. This is unfavorable for the analysis of cavities made of Nb_3Sn, which is a promising material for future SRF cavities as it allows the operation at 4.4 K [3]. In addition, Allen-Bradley resistors exhibit systematic temperature deviations after performing several temperature cycles [2]. Thus, it reduces their suitability for use in experiments studying effects during transition to the superconducting phase, in which several temperature cycles are often performed.

In this paper, the search for advanced temperature sensors that combine the high-precision of Cernox sensors and low-cost of Allen-Bradley resistors is presented. Building on the results of [4], various commercially available semiconductor components are studied. The components are analyzed with respect to the following parameters: In order to achieve high sensitivity, a strong dependence of the electrical response on temperature is needed. Additionally, a high response speed is required in order to detect quick effects. Also, high reproducibility is desired.

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[1] Temperature sensors from the manufacturer LakeShore.

EXPERIMENTAL SETUP

For the analysis of the mentioned properties at cryogenic temperatures, a two-stage cryo-cooler is used. In an isolation vacuum it can reach temperatures down to about 6 K. A round copper plate is mounted onto the cryo-cooler, on which a Cernox sensor for calibration and two semiconductor components to be tested are screwed. A heater foil glued to the cryo-cooler and driven by a PID controller allows for precise temperature control (see Fig. 1).

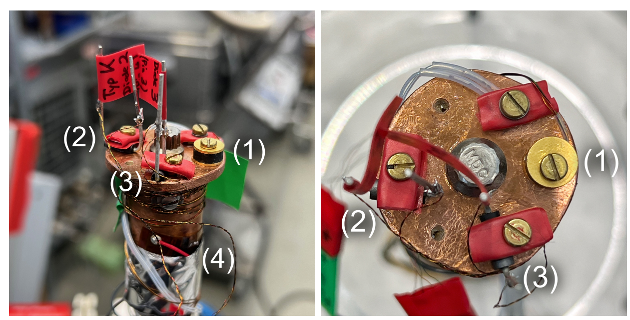

Figure 1: Photographs of the experimental setup. A copper plate is mounted onto the cryo-cooler on which the Cernox sensor (1) and semiconductor components (2)&(3) are screwed. The heater foil (4) is glued onto the cryo-cooler below the plate.

The following commercial semiconductor components have been tested (see Table 1). Among them are both LEDs and diodes.

All tested components have an insulating casing (i.e. the casing of LEDs or the cylindrical housing of wired diodes), which lowers the thermal conductivity between the copper plate and sensor and thus could have an impact on response speed. Therefore, the wired diodes are polished until the semiconducting material has direct contact with the surface. In order to avoid a short between the diode and the copper plate, the diode is insulated with a thin layer of varnish. This grinding process is not possible for LEDs, as the wirebonds inside the insulation will be damaged immediately.

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Table 1: Tested Semiconductor Components. For diode A and D the manufacturer cannot be determined.

Type	Manuf.	Model / Item Number
Diode A	Unknown	1N4007GEG
Diode C	ITT	1N4007GEG
Diode D	Unknown	1N5818
LED G	Osram	GW QTLTS2.QM-GWH5-XX58-1-65-R33
LED H	Osram	GP JTLPS1.14-M2N1-P1P2-1-150-R33
LED I	Kingbright	KP-3216MGC
Diode K	onsemi	1N5359BG
Diode M	Vishay	1N5408-E3/54
Diode N	Vishay	GP02-40-E3/54
Diode R	DiodesZetex	B360A-13-F

MEASUREMENT PROCEDURE

As electrical response, the voltage drop for a constant current (mostly [2]) of 10 µA is measured using the four-wire sensing. For the voltage measurement a time resolution of 500 ms is reached using the 34465A Multimeter by Keysight [5]. The Cernox is read out by the Model 336 Cryogenic Temperature Controller by LakeShore [6]. For every data point 20 measurements are performed with 2 Hz sampling rate.

First the voltage is measured as a function of temperature. The data allows the sensitivity to be calculated, which is defined as the change in voltage per temperature difference. Also the measurement data can be used as calibration in order to convert the voltages into temperature values in later measurements. The response speed is measured in the second to minute timescale by performing temperature cycles.

Furthermore, promising diodes are tested for reproducibility. For this purpose, 200 – 500 temperature cycles between 7 K and 20 K are performed while measuring the temperature deviation at 7 K after each cycle.

RESULTS

Sensitivity

The component voltage is measured as a function of the temperature in the range from 6.5 K to about 22 K in steps of 0.1 K with thermal equilibrium achieved in every step. The results are shown in Fig. 2. For comparison the voltage of a Cernox CX1050 [7] and an Allen-Bradley resistor [2] is plotted as well.

For most tested components an increasing voltage for a decreasing temperature can be seen. Diode A, M and N exhibit a non-monotonic increase in voltage, resulting in an ambiguity in temperature if used as sensors. Thus, they are inappropriate for use as wide-range temperature sensors. All analyzed LEDs show a linear increase in the entire

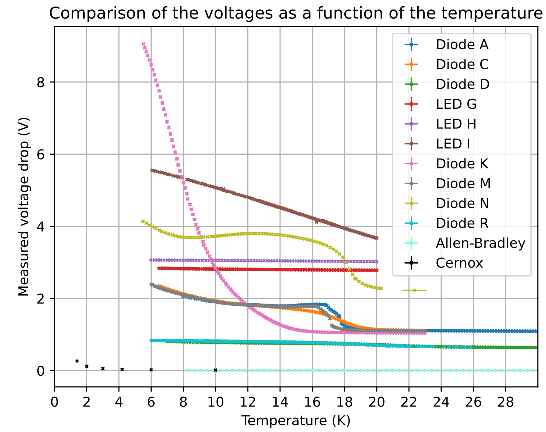

Figure 2: Voltage drop as a function of temperature. Almost all components are operated at 10 A. Diode K is operated at 1 A. Most components show a monotonic increase in voltage for lower temperatures. Diode K exhibits the strongest increase in voltage for decreasing temperatures.

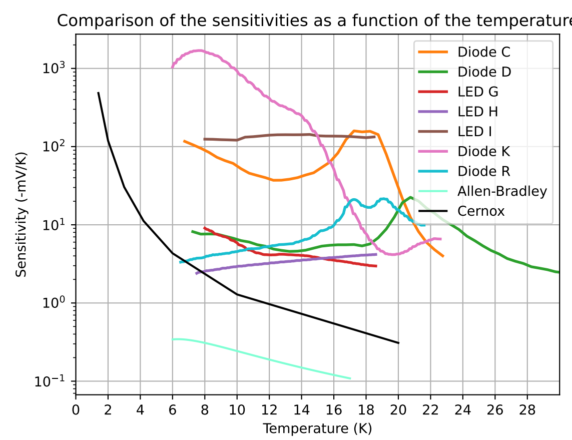

Figure 3: Sensitivity as a function of temperature. Note the logarithmic scaled y-axis. Only components with a monotonic $V-T$ curve (see Fig. 2) are shown. Diode K exhibits the highest sensitivity below 15 K.

temperature range, which is a convenient behavior for calibration purposes. Contrary to expectation the same type of diode exhibits different $V-T$ curves dependent on the manufacturer, e.g. diode A and C. In Fig. 3 the sensitivity as a function of temperature is shown for all semiconductor components with a monotonic $V-T$ curve. The sensitivity curves of a Cernox CX1050 and Allen-Bradley resistor are plotted as well. Diode K has the highest sensitivity for temperatures colder than 15 K compared to all other components (max. 1700 mV/K at 7.6 K). At 7.6 K the sensitivity is more than 500 times higher than the Cernox' sensitivity. LED I shows a constant sensitivity of about 130 mV/K in the whole analyzed temperature range and hence is a candidate as a general-purpose sensor. This is also the case for diode C, which has a sensitivity higher than 30 mV/K for temperatures lower than 20 K. The behavior of the curve

[2] Diode K is operated at 1 µA.

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also suggests an increase in sensitivity for temperatures below 6 K. Compared to Allen-Bradley resistors, which have a sensitivity of max. 0.34 mV/K, almost all tested semiconductor components show several orders of magnitude higher sensitivity in the tested range.

Response Speed

The response speed is analyzed by performing quick temperature changes between 7 K and 20 K. Meanwhile the Cernox temperature and the voltage of the components are measured with a sampling rate of 2 Hz. Afterwards the voltages are converted into temperature values with the use of the $V - T$ curves obtained before in order to compare the components output with that of the Cernox with respect to time. Overall, only two different behaviors are determined, which only depend on the type of semiconductor used – diode or LED. One representative curve for each type is shown in Fig. 4.

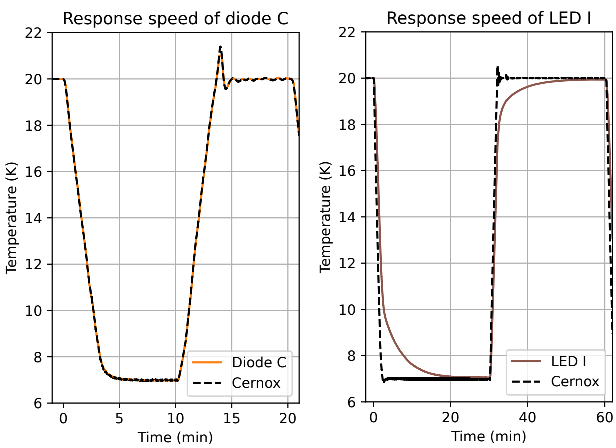

Figure 4: Response speed of diode C and LED I compared to the Cernox. Note the differently scaled x-axes. No difference between Cernox and diode is visible. The LED reacts slow to temperature changes.

In the plotted scale the temperature values of the diodes (here diode C) are indistinguishable from those of the Cernox. A more precise comparison of the maxima, caused by the behavior of the PID controller, leads to a time difference of less than one second. Since this corresponds to the magnitude of the sampling rate, a readout device with a higher sampling rate is required for a more precise measurement.

The LEDs (here LED I) exhibit a different behavior. Even though the LEDs show a change in output with a very small delay in the event of a strong temperature change, the sensor only slowly approaches the temperature value of the Cernox sensor. This value is displayed after about 20 minutes. This behavior is inappropriate for use as a temperature sensor since quick effects cannot be resolved.

The most likely cause of the two different performances is the insulating housing of the LEDs. As discussed before, wired diodes can be polished, but LEDs cannot, which leads to poor thermal contact and thus large timescales to reach thermal equilibrium.

Reproducibility

Some promising semiconductor components are analyzed in terms of reproducibility. For that, 200 – 500 temperature cycles between 7 K and 20 K are performed. After every cycle the voltage is measured at 7 K once a thermal equilibrium is reached. The voltages converted to temperature as a function of the number of cycles are fitted linearly. The slope represents the temperature shift rate and thus a measure of reproducibility. In Fig. 5 the temperature deviation of LED H as a function of the number of cycles is shown. A linear fit is added.

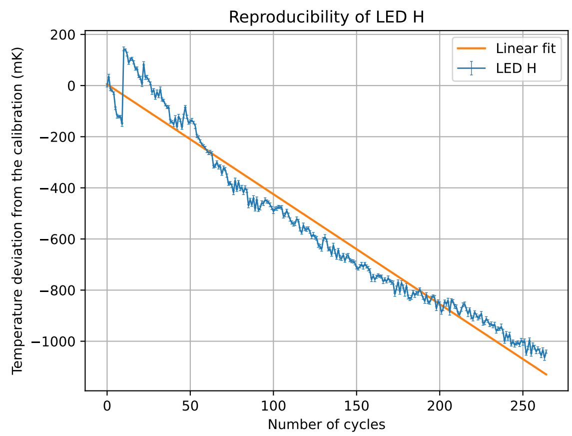

Figure 5: Temperature deviation of LED H from the calibration as a function of the number of cycles. A linear fit is added.

It can be seen that the absolute deviation in temperature increases almost monotonically. Slight variations may be caused by an inaccurate set temperature by the PID controller. After 250 cycles LED H exhibits a deviation of about 1 K.

In Table 2 the linear shift rate of different tested components is listed.

Table 2: Temperature Shift Rate of Different Tested Semiconductor Components

Type	Temp. Shift Rate (mK/100cycles)
Diode C	1.2 ± 0.3
LED H	-347 ± 4
LED I	-260 ± 8
Diode K	-2.6 ± 0.4
Diode M	0.9 ± 0.6
Diode R	-61.4 ± 0.9
Allen-Bradley	-281 ± 6

It can be seen that Diode C, K and M have a small linear temperature shift rate and thus high reproducibility. Diode R shows noticeable temperature deviations with increasing number of cycles. LED H, LED I and Allen-Bradley resistors exhibit the highest linear temperature shift rate and thus poor reproducibility.

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Hence, Diode C, K and M are suitable for use as sensors in experiments performing several temperature cycles, while LED H, LED I, Diode R and Allen-Bradley resistors show strong systematical deviations in temperature after performing cycles and thus are inappropriate for use in such experiments.

CONCLUSION AND OUTLOOK

The experimental results allow to identify some diodes that are suitable for sensors at cryogenic temperatures. While LEDs can be ruled out for use as sensors due to their high response time, none of the diodes has this limit. The most promising diode is type K, which has the highest sensitivity in temperatures below 15 K with a maximum of 1700 mV/K at 7.6 K. Compared to Cernox sensors, at this temperature the sensitivity of diode K is more than 500 times higher. In addition, diode K exhibits good reproducibility. The second diode suitable for temperature measurements is type C, offering a high sensitivity of 35 mV/K to 160 mV/K below 19 K and even better reproducibility.

In future experiments, both promising diodes should be tested in a cryostat at 1.8 K to find out their suitability for analysis of current niobium cavities. Since all measurements so far have been performed in vacuum, the effects of superfluid helium on the diodes are unknown. This could affect the reproducibility of the sensors.

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