Common rectifier diodes in temperature measurement applications below 50 K

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Abstract. In this paper we studied the use of common electronic semiconductor diodes in temperature measurements at cryogenic atmosphere. The motivation for this is the high price of calibrated cryogenic temperature sensors since there are some applications, like quench detection, in which a cheaper and a less accurate sensor would suffice. We measured the forward voltage as a function of temperature, $V_f(T)$, of several silicon rectifier diodes to determine the accuracy and interchangeability of the diodes. The experimental results confirmed that $V_f(T)$ of common rectifier diodes are similar to cryogenic sensor diodes, but the variability between two samples is much larger. The interchangeability of the diodes proved to be poor if absolute temperatures are to be measured. However for sensing changes in temperature they proved to be adequate and thus can be used to measure e.g. quench propagation or sense quench ignition at multiple locations with cheap price.

1. Introduction
Cryogenic thermometers and their sensing elements are generally expensive due to the need for individual calibration and long term accuracy. These commercial sensors, like the Cernox$^\text{TM}$ sensors for high field applications or the rhodium-iron sensors for accurate second standard measurements, are needed in cryogenic measurements to provide accurate and reliable overall data of the sample temperature. [1] In some cases there is, however, a need for a small and cheap sensor to be used only for a few times. An example of this is a quench propagation measurement, where the quench propagation velocity can be determined from the transient temperature distribution. To measure this fast process, a small sensor with fast response must be used. Also, the sensor should be mounted firmly to minimize any temperature differences between the sample and the sensor.

Diodes are often employed in cryogenic applications requiring good interchangeability of sensors in the 40 K and below temperature range. However, the measurement accuracy decreases significantly when external magnetic field is applied to the sensor. [1] Diodes made for cryogenic sensor applications are in general much cheaper than other commonly used sensors, but still they cost more than a 100 $ a piece. [2] For a cheaper alternative, the use of common rectifier silicon diodes has been studied in [3, 4]. We decided to pursue a similar path and studied the use of modern surface mount device (SMD) diodes as temperature sensors. This approach was chosen since SMD devices are very small. The main challenges in using general electronic components as temperature sensors are the possible inaccuracy due to manufacturing tolerances and the uncertain ability of the component to survive thermal cycling.
common electronic diodes is an unknown factor and some unexpected anomalies caused by the low operation temperature may be present. The theory on the behaviour of p-n-junctions at low temperatures is discussed in [5,6] and will not be scrutinized in this paper.

2. Diode as a temperature sensor

Electronic temperature sensors function by converting a change in temperature $T$ to a measurable change in some electrical material property, usually potential difference or resistivity. Potential differences can be measured directly with modern digital multimeters and changes in resistance are easily converted to potential differences using the Ohm law. When diodes are used as thermometers, the measurement procedure is almost the same as with the resistive sensors. The only difference in the measurement setup is the polarity of the sensor element. To be used as a temperature sensor, the diode must be forward biased i.e. the positive polarity of the excitation current must be connected to the anode of the diode.

The forward voltage $V_f$ of the diode depends on the sensor temperature and by measuring $V_f$ the temperature of the semiconductor can be determined. $V_f(T)$ curves of diodes are in general very nonlinear. Sensitive voltage meters can measure changes in the forward voltage of the diode at room temperature and the increase in $V_f$ with decreasing temperature can be approximated with a linear equation to around 60 K. In temperatures below 40 K the nonlinearity is more prominent and the sensitivity of the sensor increases.

When diodes are used as temperature sensors the forward voltage of the diode is measured at a constant current. Due to the high forward voltage, around 2.5-3.5 volts at 10 K, the current used must be very small in order to minimize self heating effects. In our experiments we used 10 $\mu$A for the excitation.

3. Experiment and computations

We performed two different experiments to assess the accuracy and interchangeability and to measure the transient response of the diodes. The measurements were performed in a conduction-cooled measurement system. BAS16 diode, an SMD variant of 1N4148 diode, was chosen for the experiments. The choice was based on the results reported in [3] for the BAS16 diode. A 2D transient heat transfer finite element model was used to provide some computational reference for the measurements.

3.1. Accuracy and interchangeability

To determine the absolute accuracy of the diodes in a temperature sensing application, a calibrated and reliable sensor had to be used as a reference. We used a calibrated Cernox CX-AA sensor for the calibration measurements. For this experiment, the diodes were mounted with cyanoacrylate glue to a copper block made from high purity copper. The reference sensor was fastened to the same block. This assembly was then bolted to the cooling contact. The configuration is visualised in figure 1.

The calibration was performed by measuring $V_f$ of the diodes and the resistance of the Cernox sensor using a multiplexer unit and two multimeters. The calibration consisted of three phases. First $V_f(T)$-characteristics for the cooldown were recorded. Then the temperature was cycled between 11 and 50 K in 5 K steps while recording the $V_f(T)$ of the diodes. This cycling was then repeated several times. Finally $V_f(T)$-characteristics were measured during warm-up.

The interchangeability of the diodes was studied by measuring several BAS16 diodes. From the $V_f(T)$-curves measured for individual diodes, a mean $V_{f,\text{mean}}(T)$-curve was then computed. The individual $V_f(T)$-characteristics were then compared with the $V_{f,\text{mean}}(T)$-curve. The interchangeability was then evaluated from the difference between a $V_f(T)$ and $V_{f,\text{mean}}(T)$.
3.2. Transient response

To measure the transient response, a calibrated sensor had to be used as a reference. We chose to use the same type of Cernox sensor that was used in the calibration measurements. A bare Cernox sensor chip or one in the hermetic plastic package would have been better suited to this application as their internal response time is lower than the CX-AA sensor [7]. For these experiments we did not have access to the faster types, but as we wanted to compare the response of the diodes to a commercial sensor we had used in many application, the slower CX-AA could also be used.

For measuring the response time of the diodes, we used a copper sample with known dimensions. The sample was cooled from one end, and a heater was mounted to the adiabatic end. Sensors were then mounted to the copper sample and the distances from the cooling contact, heater and between the sensors were measured. The diodes were again glued in place and the Cernox sensors were mounted to copper cylinders soldered to the sample. The entire sample was surrounded by a copper radiation shield. The radiation shield was cooled by mounting it to the cooling contact from the upper end. The setup is illustrated in figure 2.

The transient response was measured by observing the time differences in the change in the readout of the sensors. The transient was initiated by energizing the heater with a known amount of energy. The readouts of the sensors were then recorded at a fixed sample rate. The measurement was repeated several times and at different temperatures. In this measurement both the diodes and the CX-AA were excited using a constant current source set to 10 $\mu$A and the sensor values were recorded using the multiplexed voltage meter system presented in the previous section.

![Figure 1. Calibration measurement setup.](image1)

![Figure 2. Transient measurement setup.](image2)

3.3. Modelling and computations

Transient response of the sensors was simulated by solving the heat diffusion equation

$$\nabla \cdot (\lambda \nabla T) + Q = C_p \frac{\partial T}{\partial t},$$  \hspace{1cm} (1)

where $\lambda$, $T$, $Q$ and $C_p$ are the thermal conductivity, temperature, volumetric heat generation and volumetric specific heat, respectively. The 2D geometry and boundary conditions for the computations is presented in figure 3. We used Comsol [8] for the finite element method simulations and Matlab [9] for the post-processing and data handling. The dimensions of the model and the parameters for the simulations were matched with the measurements. As the real experiment used oxygen free copper in all parts, thermal properties of OFHC RRR=100 copper from [10] were used for the computations.
Figure 3. 2D geometry and boundary conditions for simulations. Here, $\lambda$ is thermal conductivity, $T$ is temperature and $Q(t) = \begin{cases} Q_0 & t_1 < t < t_2 \\ 0 & 0 < t_1, t > t_2 \end{cases}$, where $Q_0$ is volumetric heat generation and $t$ time.

To compute the transient response, the simulated $T(t)$-graphs were observed from two points representing the actual sensor locations. These graphs were then subjected to the same analysis as the experimental data.

4. Results

4.1. Calibration

The results from the calibration measurements are presented in figure 4. The data presented in the figure is a compilation of measurement results for 2 cooldowns (room temperature to 12 K) and 6 sweeps between 12-50 K (3 sweeps per cooldown). Variation in $V_{f,\text{mean}}(T)$ was not observed between cooldowns or sweeps.

![Figure 4. Temperature dependence of the diode forward voltage. Inset shows only $V_{f,\text{mean}}$ from 15 to 270 K. Legend: —— D1, —— D2, —— D3, ····················· D4, —— $V_{f,\text{mean}}$ fit](image)

The interchangeability of the diodes can be evaluated from figures 4 and 5. As can be seen, the common rectifier diode BAS 16 is not suitable for an accurate absolute temperature sensor. The deviation from $V_{f,\text{mean}}(T)$ between the four sample diodes is significant, about $\pm 0.8$ K at 20 K, and increases as the temperature decreases. Also sawtooth waveform oscillation of $V_f$ with temperature dependent amplitude was found to cause increasing error when the temperature was lowered below 18 K. This can be explained by noise induced into the excitation current as presented in [11], but the sharp sawtooth waveform and 3 kHz frequency indicated that at least the 50 Hz power line noise was not the source.

The sensitivity of the diodes is presented in figure 6. In our applications, we require that changes greater than 10 mK are detected. The specifications for our multimeters state that resolution, for sample rates up to 4.4 kHz, is 10 $\mu$V at worst [12]. Therefore the sensitivity of the sensor has to be 1 mV/K or greater. The sensitivity was found to be sufficient for our applications, as it varies from 3 mV/K at 40 K to 100 mV/K at 20 K. This temperature range is of great interest since MgB$_2$ enables relatively cheap superconducting magnet applications in 0-3 T range around 20 K. The adequate sensitivity makes it possible to get good measurement signal from a transient measurement also for small changes in temperature and thus sensing disturbances in DC use. One of our next challenges is to measure sensitivity at applied magnetic fields.
4.2. Transient response

First, the transient response of the diodes was evaluated from the change of $V_f$. Three initial temperatures $T_{\text{init}}$ of 20, 25 and 30 K were used in the experiments and a 6 joule energy pulse was used for the transient initiation. The pulse duration was fixed to 450 ms. Figure 7 presents $V_f$ response of diodes for $T_{\text{init}} = 20$ K. Standard deviation of the noisy constant section at the beginning of the unprocessed measurement data at 20 K was used as the criterion to determine the total response time of the sensor setup. The standard deviation $\sigma$ was found to be $3.67 \times 10^{-4}$ mV and a criterion of $2\sigma$ was chosen. This corresponds to temperature raise $\Delta T$ of 16 mK. The response time of the measurement presented in figure 7 was 130 ms for diode 1 and 380 ms for diode 2 measured from the start of the heat pulse.

To evaluate the response of the diodes, it was compared with a calibrated sensor. For this we used the described Cernox. The temperatures given by the diodes were computed from inverse $V_{\text{mean}}(T)$. The data were then offset corrected to help in the comparison and the $\Delta T$ criterion of 16 mK was selected again to give the response time. Figures 8 and 9 present the measured temperatures, including the ones obtained from the FEM computations, of the lower, i.e. the end with the heater, and the upper end, respectively, when the heater was energised from 2 to 2.450 s for injecting the 6 J heat pulse.

The simulated results were chosen for the basis in evaluating the response of the sensors. The results are presented in figures 10 and 11 for the lower and upper sensors, respectively. For reference the response times of the computational model are also presented. These times were...
determined from the beginning of the disturbance to the fulfilment of the 16 mK criterion. The computational response was so fast at the lower end, that for clarity, only the longest of the times is presented in figure 10. The simulated response time for the lower end were 1, 6 and 8 ms and for the upper end 22, 44 and 81 ms at temperatures 20, 25 and 30 K, respectively. The measured response times of the lower end sensors were much longer, e.g. 62 ms for Cernox and 142 ms for diode when $T_{\text{init}} = 20$ K. The same response times for the upper end were 121 ms for Cernox and 382 ms for diode.

These results indicate that the commercial and much larger Cernox sensor is faster than the small and cheap rectifier diode. This would seem to be counterintuitive since the diode is much smaller than the Cernox. The mass of the Cernox sensor is $\sim 390$ mg [2] and the diode was weighted to have a mass of $\sim 10$ mg. Therefore the most probable cause for this behaviour is the encapsulation material of the diode as it is made from epoxy with silica filler having low thermal conductivity.

5. Conclusions
The common rectifier diode is a viable alternative for a calibrated commercially available cryogenic temperature sensor in applications where absolute accuracy is not necessary. The
diode is an adequate choice for a relative temperature sensor in the temperature range of 20-40 K. In this range the sufficient sensitivity provides a clear and good measurement signal. It was discovered that although the diode is 39 times lighter than the commercial Cernox sensor, its response time is longer, but still adequate for measuring a transient phenomenon. In the scope of this work it was not tested if removing some of the encapsulant provides an improvement of the response time, but this approach will be studied in the future.

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