PERFORMANCE CHARACTERISTICS OF SILICON DIODE CRYOGENIC TEMPERATURE SENSORS

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ABSTRACT

Performance characteristics with current technology for silicon diode temperature sensors are outlined and data presented which illustrates the commonly encountered problems associated with their use. The packaging which resulted in a wide range, hermetically packaged diode sensor is presented. Data on the matching characteristics and reproducibility of the sensor are discussed. In addition, a means of enhancing accuracy over the temperature range from 50K to 335K to better than 0.15K with the aid of a two point calibration is illustrated.

INTRODUCTION

Diode temperature sensors have been in use for over thirty years and have become firmly established as rugged and reliable temperature sensors. The popularity of diode sensors is due to the advantages they offer over alternate forms of thermometry; wide range, high sensitivity, high signal level, ease of use, and inexpensive operation. Several papers cover these aspects in detail.[1,2,3,4,5,6,7,8,9,10,11,12,13]

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Diode sensors historically have been available in a wide variety of packages and package configurations. The practice of potting the diode chip in epoxy or potting a glass encapsulated commercial diode was the consequence of the demand for small, low thermal mass sensors. These configurations also permitted the small manufacturer to make small quantities of sensors by hand, which was necessary in the developing years of the cryogenic sensor market. In this "traditional" diode package, the sensing element itself was usually in intimate contact with the epoxy or glass. Thermal expansion mismatches between the epoxy or glass package and the diode sensing element could result in instabilities of the temperature sensor with time. In addition, the poor thermal properties of the materials used in the package construction are detrimental to the overall performance and reliability of the temperature sensor.

This paper first presents self-heating data taken at Lake Shore Cryotronics, Inc. on an epoxy encapsulated diode package to illustrate what aspects are critical in the design of a temperature sensor and how they influence performance. A thermal design is then presented which addresses these issues and supporting data illustrating the device performance are given. In addition, current design and understanding of the silicon diode sensing element allows the user to select a Lake Shore silicon diode sensor and, with a two point calibration, achieve accuracies which approach 0.1K over the temperature range from 50K to 335K.

SELF-HEATING

Self-heating in a sensor refers to the situation where the power dissipated in the sensor causes the sensing element to locally warm to a higher temperature than its package and/or surrounding environment. Self-heating is especially critical in cryogenic temperature sensors because thermal conductivities near liquid helium temperatures may be smaller by orders of magnitude than they are near room temperature. Self-heating in a sensor is not necessarily bad as long as the effects due to the self-heating are reproducible and create minimal temperature uncertainties. Unfortunately, they usually are not, and heat flow from and to the sensor must be carefully considered.

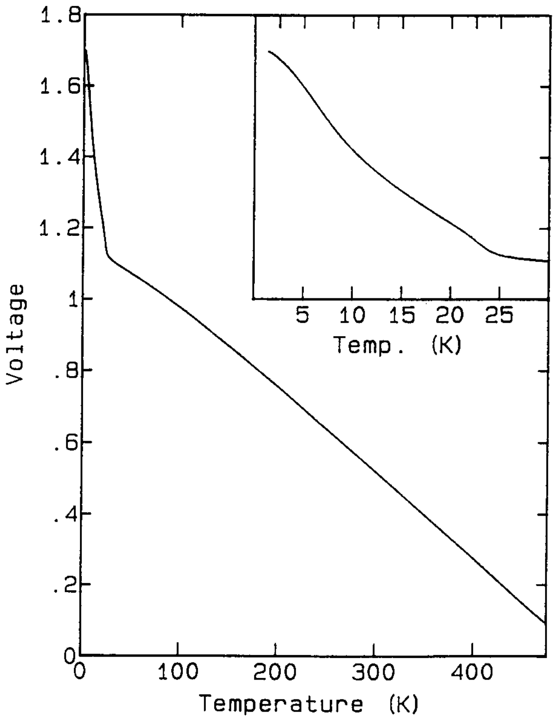


Figure 1. Voltage characteristic of the silicon diode temperature sensors discussed in the text.

Self-heating of the junction in a silicon diode sensor is unavoidable due to the relatively high power levels at which the sensor is operated. A typical silicon diode sensor, at 4.2K with a bias current of 10 microamperes, dissipates approximately 20 microwatts (Figure 1), which is nearly three orders of magnitude larger than the typical power dissipation associated with reading a 1000 ohm germanium resistance temperature sensor at the same temperature. Consequently, the potential for self-heating errors in diode thermometry makes the packaging and mounting of the diode extremely critical to its overall performance and reliability as a temperature sensor.

Self-heating tests for resistance sensors are straight forward. At a given temperature, the current is set and the resultant voltage is measured. The calculated resistance (V/I) should exhibit no current dependence. Any deviation in measured resistance at constant temperature with increasing current is the result of self-heating and, hence, the associated temperature error for a given current level is readily measurable. However, the forward voltage for a diode has a non-linear relationship with current, and self-heating is not as easily measured.

SELF-HEATING TEST RESULTS

Two different tests have been developed for examining the self-heating effects in diode temperature sensors. The first test involves mounting the diode sensors onto an isothermal copper block as they would normally be mounted in use. Calibrations against germanium resistance thermometers are carried out below 4.2K with the block first submerged and directly in contact with a pumped helium bath (tops of sensors exposed to liquid). The sensors are then recalibrated with the copper block mounted in a vacuum. A thermal link is used between the copper block and the bath to provide the necessary cooling. This test exposes mounted sensors to two drastically different thermal environments. Note that the sensor is never dismounted during the course of these tests. An ideal package design would result in no difference in temperature measurement between the two calibrations described.

Averaged results for the vacuum/liquid calibration comparison for a group of 5 miniature epoxy encapsulated silicon diode sensors are shown in Figure 2. The temperature range is between 1.5K and 4.2K and current excitations are 1, 10 and 100μA where the deviation from the corresponding vacuum calibration is shown on the vertical axis. The sensors indicate a warmer temperature when mounted in vacuum. As expected, self-heating induced errors increase as the excitation current is increased. This current-dependent trend is fairly typical of all diode packages examined, except that the sapphire-based hermetic package suffers about a factor of ten less offset than the less efficient designs.

The results in Figure 2 indicate that the solution to the power dissipation problem would be to reduce the operating current to 1μA, but this raises the static impedance of the diode into the megohm range, which lowers the signal-to-noise ratio, resulting in tighter constraints on the measurement electronics as well as the care required in shielding (installation) of the sensor and its leads.[14] Consequently, 10μA is a compromise associated with minimizing errors due to self-heating and errors due to noise pick-up. Some manufacturers have historically specified 100μA as the operating current in order to avoid oscillations and hysteresis in their temperature characteristics, but this current level adds dramatically to self-heating problems and is therefore not recommended.

The second test for self-heating effects requires testing for effects related to the mounting of the sensor. If a sensor can not be dismounted and then remounted reproducibly from a thermal viewpoint, self-

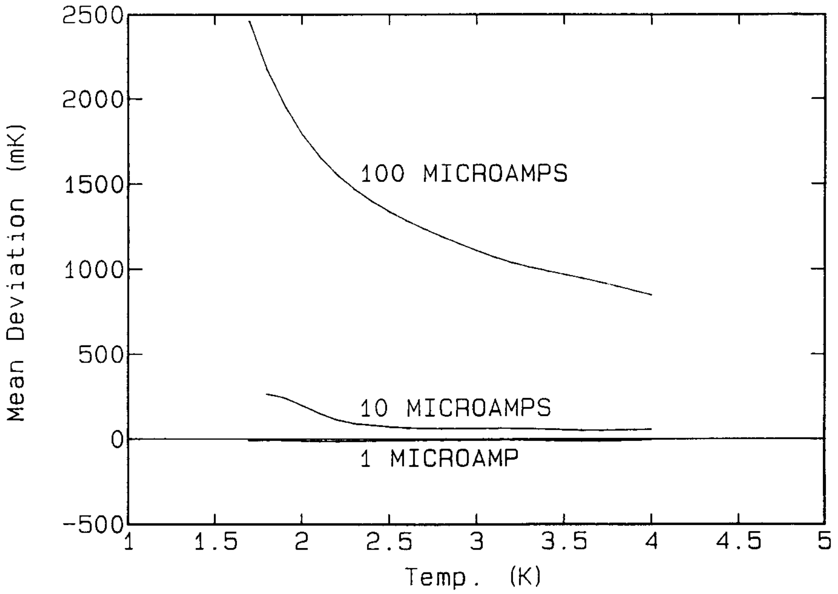


Figure 2. Self-heating comparison for a group of five epoxy encapsulated silicon diode sensors for temperatures below 4.2K and currents of 1, 10 and 100μA. Temperature error is defined as vacuum calibration voltage minus liquid calibration voltage divided by vacuum voltage sensitivity (dV/dT).

heating can generate temperature measurement errors. The best test for mounting related self-heating (the first test only examined power related effects) is to place an unmounted sensor directly in a liquid helium bath and then mount the sensor in an isothermal copper block situated in vacuum at the same temperature as the bath. This test exposes the sensor to two totally different thermal environments and two totally different mounting situations. Again, an ideal sensor should yield the same reading in both cases.

This test was conducted for 140 miniature epoxy encapsulated sensors identical to those used in the power tests above. The average voltage offset between liquid and vacuum corresponded to a temperature error of 534mK with an operating current of 10 μA. Note that this is considerably greater than the offset shown in

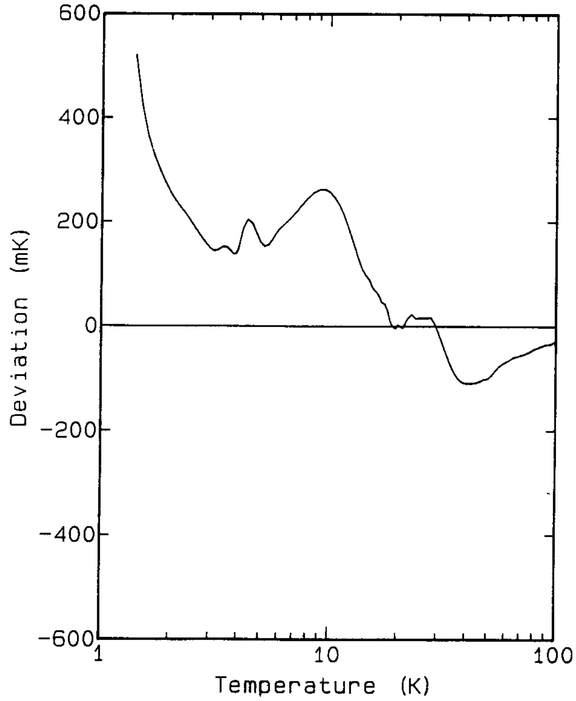


Figure 3. Epoxy Sensor - Baseline: Calibration in vacuum, sensor greased to calibration block. Second calibration in vacuum, after dismounting and remounting.

Figure 2 and demonstrates the importance of providing a means to reliably mount a sensor.

Figure 3 shows an example of the wider range deviations which can occur. A small epoxy encapsulated sensors was calibrated, dismounted, remounted, and then recalibrated. The deviation between the two calibrations below 20K can be attributed solely to self-heating and inability to reproduce the same thermal characteristics upon remounting the device. Typical vacuum/liquid offsets for epoxy/glass encapsulated diodes examined range from a tenth of a kelvin to as high as one kelvin.

THERMAL DESIGN CONSIDERATIONS

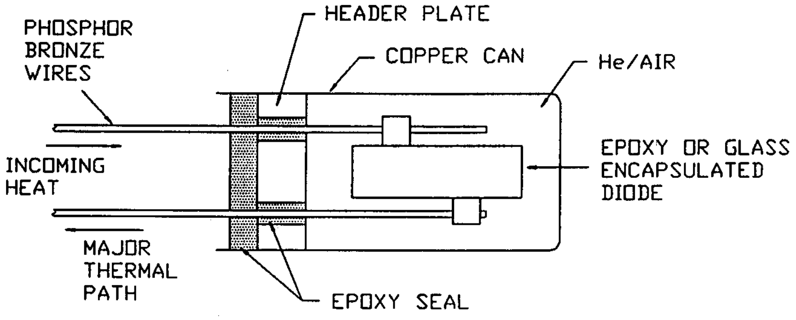
The major thermal problem with traditional epoxy and glass sensor packages is that the thermal contact between the sensing element and the outer environment is through a variety of uncontrolled thermal paths which depend on the physical potting of the device (Figure 4a). Therefore, the diode temperature sensor's response curve is dependent upon the exact mounting configuration and the conditions of the thermal environment. Since this environment will undoubtedly change from calibration to use, package design can become the most critical part of diode sensor design. One means around the mounting related problems is to calibrate the sensor in situ, but in most cases this is impossible or at least very impractical to do.

The solution to self-heating of the sensing chip is to have a sensor package with a controlled, low thermal resistance path between the sensing element and its outside environment; a thermal path which can be reliably and easily reproduced when remounting the temperature sensor. Figure 4b is a schematic view of such a sensor package.[15] Briefly, the construction details are as follows. The substrate material is single crystal sapphire, for high electrical isolation, yet good thermal conductivity. The base bottom is fully metalized with molybdenum/manganese and plated with nickel and gold so that the sensor can be readily soldered to a mounting surface. The die attach pad is fired into the sapphire and is surrounded with an alumina body. The leads are gold-plated Kovar and are thermally sunk to the substrate to minimize temperature errors resulting from heat conduction along the leads.

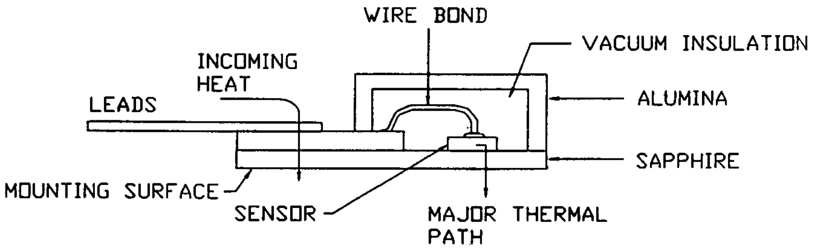
An alumina lid is sealed on under vacuum to form a moisture free hermetic seal. Since the inside of the cavity is evacuated, the sensing element is thermally isolated from the environment except through the sapphire substrate.

THERMAL DESIGN TEST RESULTS

To determine the magnitude of self-heating effects for this package design, 140 hermetically sealed diode sensors were subjected to the vacuum/liquid comparison at 4.2K described previously. The average measurement difference was 9.7mK, indicating well controlled self-heating effects.



(4a)



(4b)

Figure 4a. Schematic view of a typical non-hermetic diode package.

Figure 4b Schematic view of hermetic diode package.

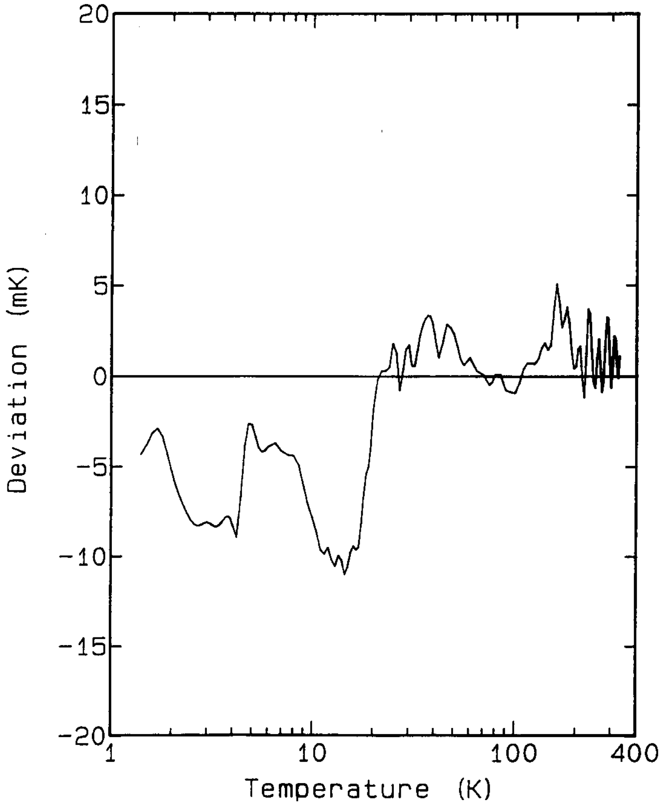


Figure 5. Hermetic diode sensor - Baseline: Calibration in vacuum, spring clipped to copper calibration block. Second calibration under same conditions after dismounting and remounting. Note scale change from Fig. 3.

Figure 5 illustrates a typical recalibration comparison for these devices when they are calibrated, dismounted, remounted, and recalibrated. The deviations are well within experimental uncertainties and indicate no self-heating effect. These results should be compared to those presented in Figure 3.

Obviously, when using commercial packages designed for room temperature applications and modified for cryogenic applications, care must be taken to understand the conditions under which the sensor was calibrated as well as having an understanding of the repeatability of the thermal path for the sensor. The hermetic package for diode sensors reduces this concern to the level of ±0.25% of T at 4.2K, i.e., ±10mk or less. This compares very favorably with some sensor/package combinations which we have measured which repeat to levels of no better than ±10% below 10K upon remounting and recalibration, yet recalibrate within about 0.1% if the mounting is left undisturbed.

INSTALLATION AND USE

The importance of properly mounting temperature sensors has been discussed in detail elsewhere and, hence, will not be discussed extensively here.[16] The important points to keep in mind when mounting any temperature sensor are: (a) maintain good thermal contact between the sensor and the sample being measured and (b) minimize the amount of heat flowing through the sensor due to radiation or conduction loads. Even a relatively large package, such as a copper bobbin, will not prevent the sensor from reading differently than the temperature of the object to which it is attached if there is a large flow of heat through the package.

The thermal installation of the leads which run to the sensor is also of primary importance. An excessive heat flow through the connecting leads to any temperature sensor can create a situation where the active element (in this case the diode chip) is at a different temperature than the sample to which the sensor is mounted. This is then reflected as a real temperature offset between the sensor and the true sample temperature. These errors can be minimized by the proper selection and installation of the connecting leads. This too, has been covered elsewhere[17,18], but the following discussion is warranted since the hermetic diode sensor package serves as its own heat sink to compensate for any heat which may be coming down the leads to the device.

As a measure of how well the devices perform as heat sinks, sensors were operated with an additional power load (typically, a few milliwatts) input to the leads near the sensor. The diodes were monitored at

Table I. Heat sink capacity of hermetic diode package in various mounting configurations and associated temperature rise at 4.2K for Copper(Cu) and Constantan(C) 36 gauge leads, each one meter in length.

MOUNTING METHOD	HEAT SINK CAPACITY(mK/μW)			Temperature Rise(mK)		
	20K	10K	4.2K		4-77K	4-300K
			NO HEAT SINKING OF LEADS			
A	1	3	6	Cu	5400	12600
				C	80	400
B	0.02	0.04	0.15	Cu	135	315
				C	2	10
C	0.005	0.02	0.15	Cu	135	315
				C	2	10
			LEADS SOLDERED TO SAPPHIRE HEAT SINK			
C	0.002	0.008	0.03	Cu	27	63
				C	0.4	2

A. Sensor physically clamped in place with grease
B. Soldered to copper adapter & inserted into hole with grease
C. Soldered to copper plate

For 36 gauge wire, the following data was assumed for temperature differences as shown:
4K - 77K - Copper (900μW/m); Constantan (13μW/m)
4K - 300K - Copper (2100μW/m); Constantan (68μW/m)

their normal 10μA excitation current and the apparent change in temperature was recorded. Several different mounting configurations were chosen for this test to illustrate the importance of heat sinking of sensor leads. The results are tabulated in Table I. The temperature rise was determined by calculating the heat flow down a 1 meter long, 36 gauge wire thermally anchored at the two temperature extremes with no additional thermal anchoring. The above table demonstrates why copper wire is seldom used for sensor applications and thermal lagging of the sensor wires is very important if temperatures near that of liquid helium are to be measured.

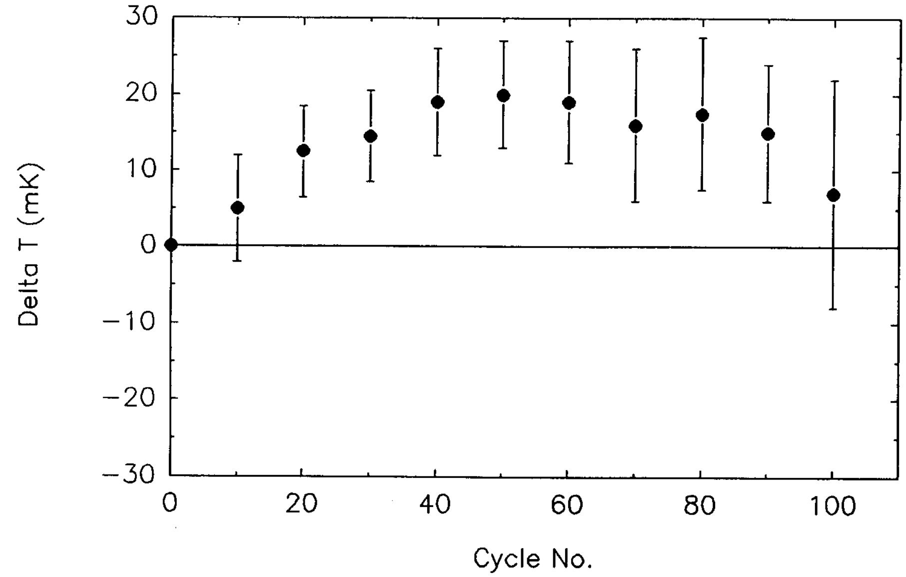


Figure 6. Short term repeatability for a group of eleven hermetic diode sensors cycled 100 times between room temperature and liquid Helium temperature. The data was corrected for temperature variation of the bath using a germanium resistance thermometer. A reading was taken every tenth cycle and compared to the first helium reading.

SHORT-TERM REPEATABILITY

To determine short term repeatability for the sensors, two different tests were conducted. First, a group of eleven hermetic diode sensors was cycled 100 times from room temperature into liquid helium. Data was measured for each sensor every tenth cycle. Figure 6 is a graphical representation of the average repeatability of the sensors at 4.2K. Deviations were calculated with respect to the first 4.2K dip value for each sensor and the results averaged. The vertical bars represent plus and minus one standard deviation. As was mentioned earlier, this test only determines short-term repeatability at a single temperature and is, therefore, not a measure of full range reproducibility.

LONG-TERM STABILITY

In order to determine the exact reproducibility or stability characteristics for the hermetic diode sensors, several groups were recalibrated periodically over an extended period of time. The devices were dismounted and stored at room temperature between calibrations. No other stress conditions were applied to them.

Figure 7 is a recalibration comparison for a group consisting of twenty sensors. The sensors were calibrated eight times over a twenty month period. The final calibrations were compared to the original calibrations to determine mean deviations as a function of temperature. The mean deviation for the group of twenty diodes is shown in Figure 7. The worst case deviations between calibrations at all temperatures between 2 and 330K were less than 50mK. In comparing recalibrations of sensors, the accuracy of the calibration itself must be considered along with the reproducibility of the sensor. Combining the stability specification of ±30mK with the calibration accuracy specification of ±20mK and an allowance for customer instrumentation errors yields an estimated worst case long term uncertainty of about 100mK. The results for this group of twenty sensors recalibrated with the same instrumentation were a factor of two better than this specification at all temperatures for all sensors.

THERMAL TIME CONSTANTS

Thermal time constants are often of importance to sensor users. Thermal time constants were measured at liquid helium, liquid nitrogen, and room temperatures for the hermetic diode sensor. Due to the package's low mass (about 35 milligrams), the response times are relatively fast. They are typically less than 10 milliseconds at 4.2K, less than 100 milliseconds at 77.35K, and on the order of a second at room temperature.

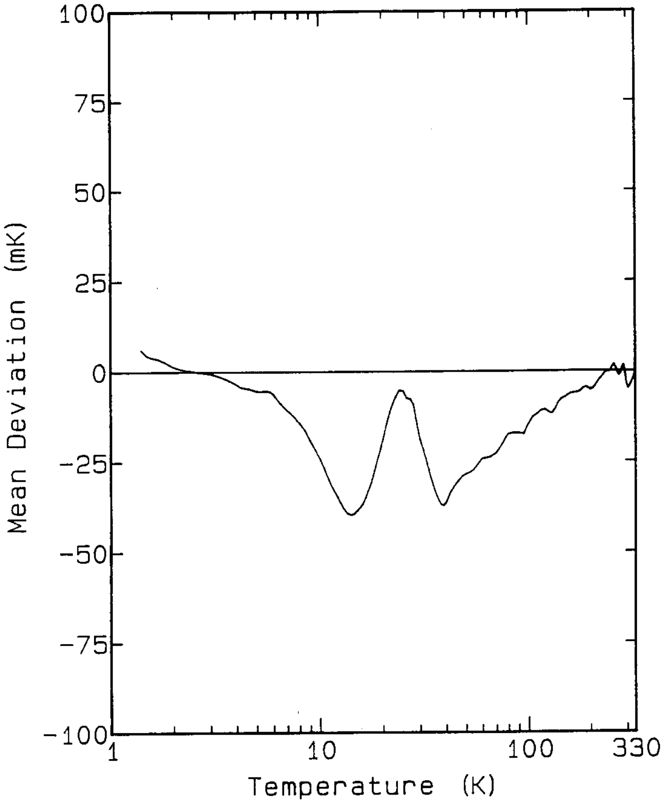


Figure 7. Mean deviation as a function of temperature for twenty sensors upon recalibration after twenty months.

CURVE CONFORMANCE/INTERCHANGEABILITY

An important feature for any temperature sensor is the uniformity between sensors and the ability to provide standardized specifications for those sensors. The ability to establish a standardized calibration curve means that individual sensor calibrations for many applications need not be performed.

Unlike the situation that exists for industrial grade platinum resistance sensors (where standardized specifications have been established), there have been a wide variety of diode voltage/temperature curves, all with slightly different thermometric characteristics, available from several different manufacturers. For platinum resistance sensors, the temperature-resistance curve is determined primarily by the platinum purity. The physics of silicon diode temperature sensors are much more complicated; the voltage-temperature characteristics depend on junction area, starting material, doping elements and their densities, junction depths, impurity concentrations, packaging and conduction mechanisms and other parameters.

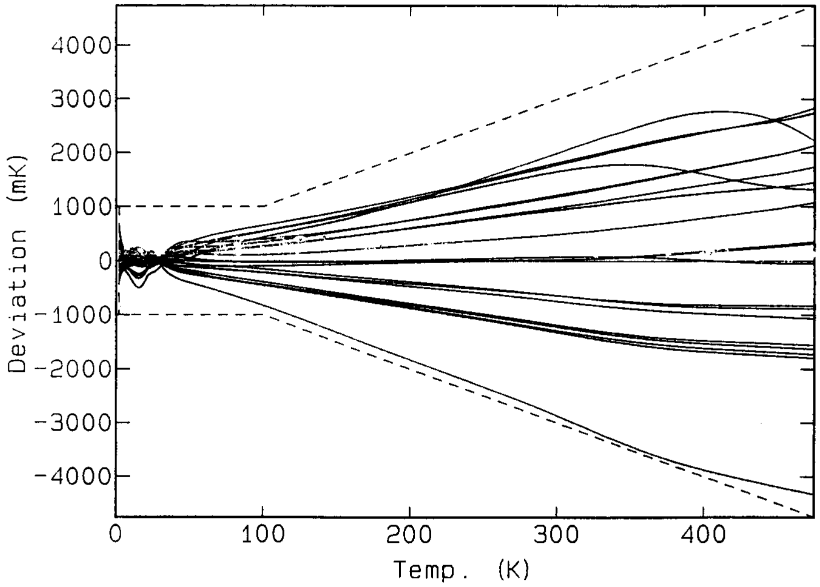


Figure 8. Deviation in temperature of several hermetic diode sensors from the standard curve over the temperature range from 1.4K to 300K.

INTERCHANGEABILITY

A standardized calibration curve is generated for diode sensor type by calibrating a large group of sensors and determining the mean curve from the calibration data. The curve shown in Figure 1 (Lake Shore Curve 10) serves as the standard curve for these diode sensors. Deviations of individual sensor calibrations from Curve 10 are shown in Figure 8. They fall within ±1K or ±1% of the absolute temperature, whichever is greater. The uniformity of these sensors in their deviation from the standard curve is of paramount importance. This uniformity allows the grouping of these sensors into tolerance bands similar to the approach used for platinum resistance thermometers.

In practice, testing of an individual sensor for conformance to the standard curve can be achieved by checking at three temperatures; liquid helium, liquid nitrogen, and room temperature, provided it has been established statistically from many calibrations that the diodes do not exceed the specified tolerances between these temperatures. As can be seen in Figure 8, the calibration curve variations below 40K can allow a sensor to be very close to the standard curve at 4.2K, but out of tolerance at lower and higher temperatures. For the diode sensors in question here, tolerances have been established for selection at the three temperatures that provide a high confidence level for tolerance band conformance over the 2K to 475K temperature range.

The closer the tolerance, the lower the proportion of sensors meeting the specifications. The closest tolerance to which reasonably large numbers of sensors can be provided is ±0.25K from 2K to 100K, ±0.50K from 100K to 305K, and ±1.00K from 305K to 475K. Higher accuracy matching can be obtained, but with higher cost and lower availability.

The highest accuracies require the sensors to be individually calibrated. It is most cost effective to calibrate a sensor that does not match the standard curve well (matching tolerances have no effect on sensor stability or other measures of sensor quality). Typically, a full range calibration will require about 60 calibration points, which is a relatively expensive and time consuming process. An intermediate calibration procedure involving a limited number of data points (one to three) is the SOFTCAL^{TM} procedure described below.

SOFTCAL^{TM} "CALIBRATION" FOR T>30K

Due to the uniform nature of the temperature characteristics of the hermetic diode sensors above 30K and the manner in which they converge at approximately 28K, it is possible to generate a precision calibration curve from only one or two calibration points with the standard curve (see Figure 1) serving as a reference curve.

Using a two point calibration measurement and a linear correction to the standard curve, the "calibration" will be given as follows:

$$V(T) = mV_{St}(T) + [V(T_1) - mV_{St}(T_1)]$$

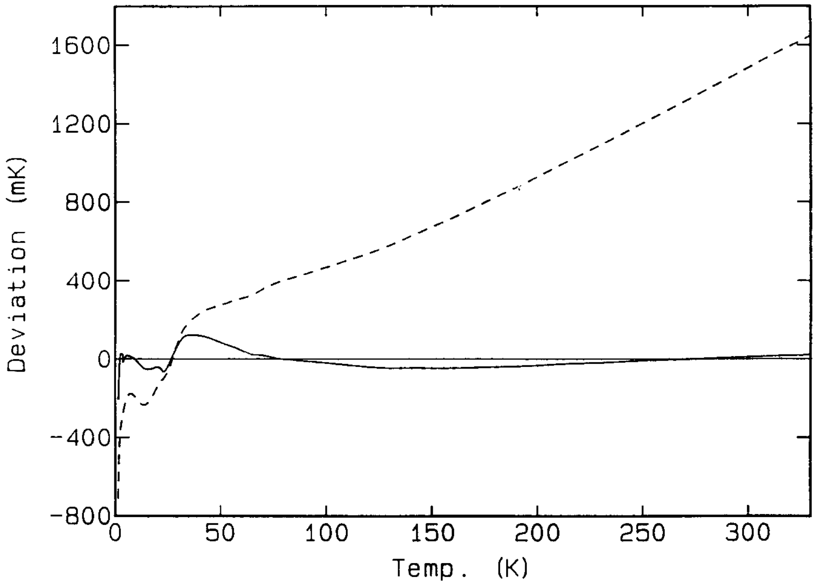


Figure 9. Effect of a SOFTCAL^{TM} "calibration". The dotted line illustrates the accuracy of a poorly conforming sensor when compared to the standard curve. The solid line illustrates the improved accuracy of the same sensor with a three-point SOFTCAL^{TM} "calibration".

with the slope m defined as

$$m = (V(T_2) - V(T_1))/(V_{st}(T_2) - V_{st}(T_1))$$

where

T_1, T_2 = known test temperatures with known voltages $V(T_1)$ and $V(T_2)$

$V(T)$ = calibration curve of sensor

$V_{st}(T)$ = Standard curve for hermetic diode sensors.

Note that m and the quantity in brackets are the slope and intercept of the correction. In use, V(T) is measured and the corresponding value $V_{st}(T)$ is determined from the equation. The standard calibration

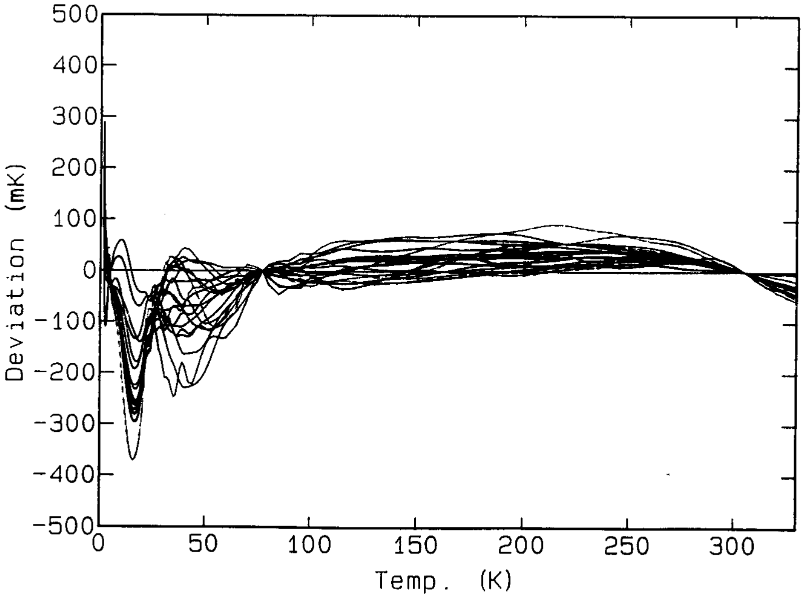


Figure 10. Comparison of a three-point SOFTCAL™ "calibration" with corresponding full-range calibrations of several hermetic diode sensors. SOFTCAL™ calibration points: 4.2K, 77.35K and 305K.

curve is then used to determine the temperature.

ONE-POINT SOFTCAL™ "CALIBRATION"

A one-point calibration will give T_2 and $V(T_2)$, but a pinning point (i.e., where the actual calibration is assumed to match the standardized curve value) is also required. The point selected is $V_s(T_1)=V(T_1)=1.111$ volts, which corresponds approximately to $T_1=28K$. This point was chosen since the hermetic diode sensors tend to converge to within ±0.25K at this point.

The selection of the calibration point is critical in determining the accuracy of the calibration. The closer the point is to 28K, the less accurate the calibration corrections become. For operation in the range T>30K, the calibration point should be chosen in the range 200<T<350K. For example, the ice point (0°C) is a convenient point. The resulting accuracy obtained using this technique is ±0.1K for a temperature span of ±40K around the calibration point, ±0.5K elsewhere in the 30 to 373K range, and ±1K above 373K. The error to which the calibration point is known must also be added to these accuracy specifications.

TWO-POINT SOFTCAL™ "CALIBRATION"

A two-point calibration requires that voltages be measured at two temperatures (T_1 and T_2) as well as defining the pinning point at 28K. To achieve the best wide range results, one calibration point should be near the ice point with the other near liquid nitrogen temperature. The resultant SOFTCAL™ "calibration" will yield an accuracy of ±0.1K between the two calibration points and ±0.2K accuracy elsewhere over the 30 to 373K range. Above 373K, the accuracy degrades to ±1K. Figure 9 illustrates such a SOFTCAL™ "calibration" for a sensor with a temperature error approaching 0.6% of temperature above 100K. The resultant two point correction above 28K improved the "calibration" accuracy to better than 100mK over the temperature range between 50K and 325K. It should be noted, however, that liquid nitrogen and ice baths do not automatically give well defined temperature points. Both can vary by as much as ±0.5K if proper techniques are not used.[19]

SOFTCAL™ BELOW 28K

The same procedure can be used for a correction to the curve below 28K. Unfortunately, a correction at 4.2K will improve the accuracy to only approximately ±0.3K at 20K. Figure 10 shows the resulting accuracy of a three point SOFTCAL™ correction for a number of calibrated sensors. The deviation indicated is the difference between the SOFTCAL™-corrected curve and the actual calibrations for a group of twenty sensors.

SUMMARY/CONCLUSIONS

An improved diode sensor package has been developed which minimizes the self-heating and remountability problems commonly encountered with traditionally packaged diode thermometers. Problems arise from self-heating as a result of either poor or inadequate thermal design of the sensor package or from improper installation of the sensor and its leads. Unfortunately, these problems are neither easily measured nor found by the user.

Due to the thermal design of the hermetic sapphire package, the sensing element responds with good independence from specific mounting configurations or the thermal environment. Self-heating or mounting related temperature errors are, on the average, reduced to the level of 10-30mK at 4.2K from levels of 0.1-1K due to previously available packages.

Efforts toward the fabrication of a uniform sensing element have yielded a diode chip with thermometric characteristics that can be matched to a standardized calibration curve to tighter tolerances than previously available. Furthermore, since the uniformity of the sensors' response is such that they conform to the standard curve over the full range of use rather than at only a few points, the specific level of curve conformance can be routinely determined by checking the sensor at the discrete temperatures of liquid helium, liquid nitrogen, and room temperature.

A method of providing improved accuracy from only a few calibration points, called SOFTCAL™, has been developed. Three calibration points can provide accuracies of 0.1K to 0.3K (plus the errors due to the inaccuracies of the calibration points) in the range from liquid helium temperatures to room temperature. This capability can be provided built into a readout instrument. The user can calibrate the sensor by simply establishing the sensor at the calibration temperature and pushing a button.

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