Low temperature thermometry in high magnetic fields. VII. Cernox™ sensors to 32 T

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This article describes the behavior of Cernox™ zirconium oxynitride film temperature sensors from Lake Shore Cryotronics, Inc. in magnetic fields up to 32 T at temperatures between 2 and 286 K. Results from a number of sensors with different dimensionless temperature sensitivities and from different production batches are analyzed and compared with previous results on carbon-glass sensors that extend to 19 T. In that field range, the Cernox™ sensors appear to be a real alternative to carbon glass. Furthermore, the magnitude of their uncorrected error, $\Delta T/T$, is smaller than other sensors at most temperatures in fields less than 20 T, and their temperature correctabilities appear to apply to off-the-shelf sensors with dimensionless temperature sensitivities in the range of -0.74 to -1.9. The sensors show a negligible (<0.05%) orientation dependence of their $\Delta R/R$ at 78 K; at 4.2 K, that dependence can be as high as ~0.7% at 20 T. © *1999 American Institute of Physics.* [S0034-6748(99)04701-2]

I. INTRODUCTION

The increasing use of higher field magnets for laboratory research has increased the need for temperature sensors that give accurate, repeatable measurements in magnetic fields up to the ~20 T available with superconducting magnets. Still higher fields are available to individual researchers with capacitor-bank-powered pulse magnets; and, of course, both direct current (dc) and pulse magnets are available in several national and international facilities around the world. An ideal sensor would be independent of magnetic field; the next best alternative would have field dependence that is small and correctable by a method that is independent of the manufacturing process. Considerable research aimed at developing sensors has been done and several commercially available sensors have been characterized.[1–5] The sensor recommended to researchers who were limited to a single sensor for the temperature range from 2 to 300 K in magnetic fields to 20 T was the carbon-glass resistance thermometer (CGRT). Now a new sensor, the Cernox™ resistance thermometer (CXRT) has been put forward as a replacement for the CGRT for a variety of reasons.[6]

Sputtered zirconium nitride films were demonstrated to be useful temperature sensors by Yotsuya, Yoshitake, and Yamamoto.[7] They have been developed into commercially available sensors by Lake Shore Cryotronics.[8] CXRTs are made by reactive sputter deposition of zirconium in an atmosphere containing argon, nitrogen, and oxygen. The temperature sensitivity of the deposited resistance film can be varied by adjusting the partial pressures of the gases during sputter deposition so that small amounts of oxygen are incorporated into the ZrN lattice. As a result, the lattice is enlarged and the electrical conductivity changes steadily with increasing oxygen content from metallic to semiconducting behavior. CXRTs are available in models with dimensionless temperature sensitivities,[9] $S_T=(T/R)(dR/dT)=(d\log R/d\log T)$, at 4.2 K from about -0.6 to about -3, indicative of increasingly semiconducting behavior.[10] Preliminary measurements of the magnetoresistance of sensors with a wide range of dimensionless sensitivities revealed that those at the extremes differed dramatically while those in the range from about -0.7 to -1.9 offered sufficient hope of being correctable to warrant further study. The goal of such a study is to supply a representative number of corrections for magnetoresistance errors applicable to "typical" Cernox™ sensors, i.e., to commercially available, off-the-shelf, calibrated thermometers. There would then be no need for users to perform their own calibrations of magnetic field effects. This study therefore focused on such sensors.

II. METHODS

Eleven CXRTs were provided by Lake Shore Cryotronics, Inc. (Table I). They were taken from nine different wafers manufactured at different times to ensure that any generalizations made about these sensors could be applied to others. Four were calibrated by the manufacturer. Nine of the sensors were encapsulated in gold-plated copper canisters (model numbers ending in AA) that placed the film surface perpendicular to the magnetic field when the canister was aligned parallel to the field. Two sensors in hermetic packages (model numbers ending in SD and LR) were used only for measuring orientation effects (see below).

CXRTs mounted in canisters have two current and two voltage leads attached by the manufacturer. Hermetically packaged CXRTs have two short leads to which we attached a total of four leads to eliminate the voltages of the long

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TABLE I. Cernox™ resistance thermometer origins.

Serial no.	Model no.	Wafer no.	Dimensionless sensitivity, S_T, at 4.2 K	Resistance at 4.2 K (Ω)	Factor calibrated
X01610	1010-AA	2Z243D	−0.747	291.3	···
X01202[a]	1030-AA	2Z255A	−0.783	480.0	*X*
X02743	1030-AA	2Z243B	−1.156	1214	···
X02007[a]	1030-AA	3Z381A	−1.196	986.7	···
X01781[a]	1050-AA	2Z245A	−1.391	1659	···
X01779	1050-AA	2Z245A	−1.446	1537	···
X03316[a]	1070-AA	3Z454C	−1.331	5483	*X*
X03564[a]	1050-AA	5Z065B	−1.349	3899	*X*
X01185[a]	1070-AA	2Z251A	−1.873	8086	*X*
X03498[b]	1050-LR	5Z065B	Not available	2530	···
X03638[b]	1050-SD	5Z065C	Not available	3810	···

[a]Sensors used in perpendicular magnetoresistance measurements to 20 T and later measurements to 32 T.
[b]Sensors used only in orientation effect measurements to 20 T.

leads extending from the sensors to the measuring apparatus. The current leads of the CXRTs to be measured in each set of measurements were connected in series in one or two groups of similar resistance. Programmable current sources were used, with the currents chosen to give sensor voltages of 1–3 mV. Self-heating errors were negligible. Each sensor voltage was measured with a precision digital voltmeter. The current was reversed at a 0.5 Hz rate and the voltage readings averaged to eliminate thermal electromotive forces (emfs). The magnetic field sweep rate was slow enough to minimize errors due to the ~0.2 Hz voltage reading rate. The magnetic field-dependent changes in voltage were recorded by a computer as the field was swept up and down and the temperature was held constant. Data were analyzed using commercially available software.

A. Perpendicular magnetoresistance

1. Measurements in fields up to 20 T

The cryostat used for perpendicular magnetoresistance measurements in fields up to 20 T had been used for previous studies of CGRTs.[1] It was designed to measure the resistance of six sensors held at constant temperature while the applied magnetic field was varied. The CXRTs and a capacitance thermometer (CT) were held in intimate thermal contact with each other by being inserted in holes drilled in a single copper block. The sensors were packed in thermally conductive grease[11] and their leads were thermally anchored to the mounting block by laying them in slots running the length of the block and packing them with grease. All the sensor leads were thermally isolated from room temperature by soldering them to short #22 copper wires glued into slots in the copper disk that supported the shield and mounting block.[1]

Steps taken to reduce eddy-current heating and to verify that isothermal conditions existed within the sample block were described in a previous article.[1] The temperature range of the measurements, 2–286 K, was covered with one cryostat by changing the cryogen bathing the outside and by varying the amount of exchange gas on the inside. Magnetic field-independent temperature control was accomplished with one of two systems, depending on temperature. At 4.2 K and below, we used a manostat to control the vapor pressure of the liquid helium in which the sample block was immersed (with the vacuum can removed); the vapor pressure was measured with a capacitance manometer. At 5 K and above, except for 78 K, a CT was used with a control circuit consisting of a capacitance bridge, a two-phase lock-in amplifier, and a proportional power controller with automatic reset. Temperature control at 78 K was by immersion in liquid nitrogen with the vacuum can removed. We took extra care to minimize the temperature shifts of a few tenths of a kelvin that are possible with columns of impure liquid N_2 in strong magnetic fields[12] by keeping the liquid column heights small and using liquid N_2 that had not been exposed to air.

The nine sensors were run in two groups. One sensor, serial number X01185, was run with both groups to ensure that the temperatures and other experimental conditions at which data were taken were the same.

2. Measurements in fields up to 32 T

Six of the nine sensors included in the perpendicular field studies up to 20 T were selected for study to higher fields. They were chosen to provide a range of dimensionless temperature sensitivities. One of the six sensors, serial number X01185, also served to ensure that the temperatures and other experimental conditions at which data were taken were the same as for all the tests to 20 T.

The cryostat used for perpendicular field measurements up to 32 T was a new design to fit into the smaller bore of the 32 T magnet. The six CXRTs were arranged in a circle around a CT with their long axes aligned and the sensor bodies touching. The sensors were held in intimate thermal contact with each other by being wrapped with dental floss. The sensor leads were all wrapped together around a G-10 post to further increase thermal contact between sensors. A slit copper cylinder 1.6 mm thick surrounded the sensor canisters and held them in alignment with the magnetic field. Heat was provided by a resistance wire heater wound noninductively on the outside of the copper cylinder. The cryostat was mounted on the end of a long stainless steel tube carrying twisted pairs of phosphor bronze wire. Steps taken to verify that isothermal conditions existed within the sample block were described in a previous article.[1] The temperature range of the measurements was limited to 2–78 K. At 4.2 K and below and at 78 K the sensors were immersed directly in liquid helium or nitrogen and the temperature was controlled and measured as described above. From 5 to 50.1 K, a CT was used as described above. However, the helium bath temperature outside the vacuum chamber was maintained at ~1.8 K for the measurements from 5 to 50.1 K to prevent helium gas bubble trapping near the magnetic field center.[13]

B. Orientation effects up to 20 T

Orientation effects were measured at only two temperatures, 4.2 and 78 K. The sensors were immersed directly in the liquid. The sensor holder used for studying orientation dependence to 20 T was a 1 in. long G-10 half cylinder cut from a 0.5 in. diam rod. Two grooves were cut in the flat face perpendicular to the magnetic field vector. The end of the sample holder was also perpendicular to the field. Selected sensors from the perpendicular field measurements were mounted on the G-10 block with their long axes perpendicular to the magnetic field. (Two were mounted in the grooves; the rest were in contact with those two.) This placed the magnetic field vector in the plane of the sensor film. However, the exact orientation of the sensor and thus of the sensor current in the film plane was not known. This orientation of the sensor current in the field is therefore referred to as "coplanar" in the discussion below.

Two sensors whose orientation within the package was known were tested to allow comparison of perpendicular ($\mathbf{j}\perp\mathbf{B}$) with parallel ($\mathbf{j}\parallel\mathbf{B}$) magnetoresistance. Both sensors, one in a SD package and one in a LR package, have the sensor coplanar with and the sensor current parallel to the sensor leads. These sensors were mounted on the G-10 sensor holder's flat face in the ($\mathbf{j}\parallel\mathbf{B}$) orientation, data were taken at 78 and 4.2 K, the cryostat was removed from the helium, the SD and LR sensors were moved to the end of the G-10 block so that they were perpendicular to the magnetic field, the cryostat was replaced in the liquid helium, and data with ($\mathbf{j}\perp\mathbf{B}$) were taken at 4.2 K.

One sensor that had been included in all three sets of perpendicular field measurements, serial number X01185, was also included in the coplanar and parallel field measurements as a control. It was mounted on the G-10 sensor holder's flat face with the canister axis aligned with the magnetic field so that the film remained perpendicular to the field. Data from this sensor were used to provide estimates of measurement uncertainty and temperature errors to which the measured orientation effects were compared.

III. RESULTS AND DISCUSSION

A. Perpendicular magnetoresistance

Perpendicular magnetoresistance data were gathered with the sensor canisters mounted with their long axes parallel to the magnetic field. Data at selected temperatures are shown in Fig. 1 for one of the CXRTs (serial number X01781). Results for the other specimens are similar up to ~20 T. For example, at 4.2 K, the maximum differences (spread) in $\Delta R/R$ among five of the six sensors measured to 32 T is only from about +2% to −1%. That variation increases appreciably above 20 T. Nevertheless, the magnetoresistance behavior is qualitatively similar to that of carbon resistance thermometers (CRTs) and CGRTs, exhibiting both positive and negative values in different temperature and field regions.

The perpendicular magnetoresistance results for all of the sensors are shown in Table II (nine sensors, B up to 20 T) and Table III (six sensors, $23\ \mathrm{T}\leqslant B\leqslant 32\ \mathrm{T}$). The results are separated into the two tables because the calculated standard deviations for the nine sensors measured only up to 20 T were smaller than for the six sensors measured up to 32 T. The upper figures in each pair of rows are the mean values of the tabulated quantities, and the lower figures are the calculated standard deviations.

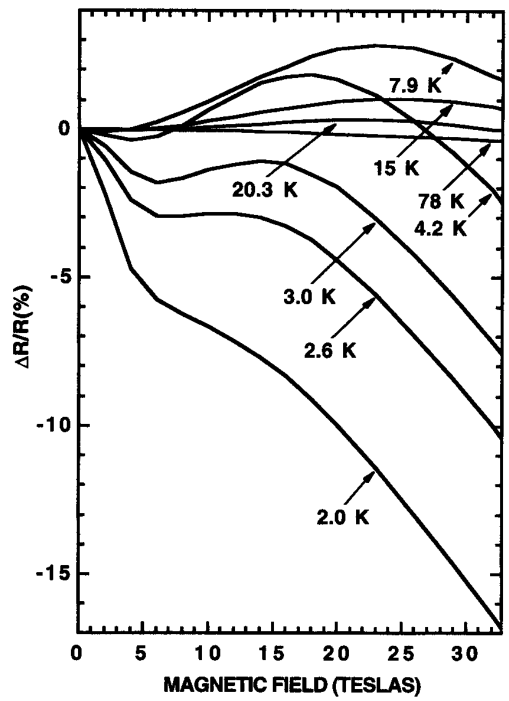

FIG. 1. Perpendicular magnetoresistance of CXRT-1781 vs magnetic field at selected temperatures. $\Delta R/R(\%)=100[R(B)-R(0)]/R(0)$.

The calculated standard deviation at each temperature and field is due primarily to differences among the sensors, and is usually much greater than the average estimated measurement uncertainty. The measurement uncertainty for each sensor at each temperature was estimated from the noise and drift during the time the field was swept. The measurement uncertainties ranged from one tenth to one half the magnitude of the calculated standard deviations at $B=20\ \mathrm{T}$ and from one tenth to one fifth at 32 T. The values of the dimensionless temperature sensitivity, S_T, from a single calibrated sensor are given as "typical" values close to the median value of the sensors used in this study.

We chose to tabulate the percentage change in resistance, $\Delta R/R$ instead of the percentage change in temperature, $\Delta T/T$, because we found the former to vary less from one sensor to another. That is, the data were examined in two different ways. First, we looked at the percentage change in resistance of each sensor as a function of field and compared the results for the whole set of sensors. Then, we converted the percentage change in resistance data into percentage change in temperature data by dividing by the dimensionless sensitivity for each sensor at each temperature. That is, $\Delta T/T=(\Delta R/R)/S_T$. The resulting standard deviations in $\Delta T/T$ were much larger because of the wide range of dimensionless sensitivities of the individual sensors and the differing temperature dependencies of the dimensionless sensitivities. For example, Table I shows that at 4.2 K the dimensionless sensitivities of the nine sensors used for the perpendicular magnetoresistance measurements varied from −0.75 to −1.87. Therefore, a researcher wishing to correct for the magnetoresistance error of a particular CXRT should

TABLE II. Magnetoresistance of nine Cernox™ sensors, 2–20 T. The values of S_T shown are those of a single sensor. They are typical values, not an average. The upper figures in each pair of rows are the mean values of the tabulated quantities, and the lower figures are the calculated standard deviations.

T (K)	Typical S_T	$\Delta R/R$ (%) as a function of T (kelvins) and B (teslas)									
		B= 2 T	4 T	6 T	8 T	10 T	12 T	14 T	16 T	18 T	20 T
2.03	−1.94	−2.137	−4.359	−5.375	−5.932	−6.413	−6.968	−7.609	−8.324	−9.182	−10.103
		0.381	1.058	1.557	1.808	1.876	1.777	1.575	1.332	1.081	0.838
2.58	−1.69	−1.038	−2.225	−2.682	−2.760	−2.799	−2.936	−3.206	−3.638	−4.205	−4.848
		0.227	0.722	1.138	1.398	1.492	1.463	1.311	1.089	0.825	0.539
2.98	−1.57	−0.613	−1.385	−1.618	−1.530	−1.389	−1.334	−1.437	−1.710	−2.124	−2.742
		0.135	0.518	0.876	1.124	1.243	1.241	1.141	0.964	0.716	0.495
3.46	−1.45	−0.390	−0.753	−0.778	−0.547	−0.247	−0.021	0.051	−0.062	−0.341	−0.711
		0.132	0.354	0.642	0.872	1.007	1.052	1.011	0.927	0.814	0.751
4.24	−1.33	−0.151	−0.269	−0.167	0.146	0.544	0.867	1.130	1.121	1.128	0.874
		0.023	0.190	0.410	0.599	0.718	0.799	0.800	0.852	0.735	0.712
5.05	−1.24	−0.089	−0.053	0.119	0.443	0.839	1.222	1.493	1.661	1.710	1.594
		0.025	0.151	0.309	0.435	0.536	0.576	0.634	0.651	0.644	0.682
5.98	−1.16	−0.081	0.016	0.207	0.506	0.896	1.288	1.610	1.854	1.998	1.961
		0.016	0.073	0.190	0.312	0.399	0.455	0.512	0.548	0.579	0.683
7.92	−1.046	−0.049	0.035	0.238	0.522	0.858	1.202	1.531	1.814	1.990	2.039
		0.024	0.031	0.074	0.136	0.187	0.247	0.303	0.369	0.487	0.620
10.38	−0.999	−0.049	−0.004	0.139	0.344	0.593	0.868	1.114	1.318	1.479	1.563
		0.024	0.036	0.056	0.086	0.121	0.148	0.199	0.290	0.390	0.504
15.01	−0.949	−0.029	−0.032	0.021	0.115	0.238	0.371	0.495	0.605	0.695	0.756
		0.015	0.032	0.045	0.058	0.076	0.108	0.150	0.199	0.263	0.330
20.31	−0.939	−0.033	−0.044	−0.047	−0.018	0.025	0.075	0.118	0.155	0.182	0.196
		0.010	0.023	0.034	0.046	0.057	0.078	0.103	0.140	0.180	0.224
30.10	−0.953	−0.008	−0.021	−0.030	−0.036	−0.041	−0.046	−0.055	−0.073	−0.094	−0.119
		0.002	0.007	0.014	0.024	0.034	0.049	0.067	0.087	0.109	0.131
50.07	−0.989	−0.005	−0.015	−0.025	−0.035	−0.049	−0.065	−0.085	−0.110	−0.139	−0.168
		0.002	0.004	0.007	0.012	0.017	0.024	0.031	0.041	0.053	0.063
77.8	−1.021	−0.002	−0.009	−0.015	−0.023	−0.034	−0.047	−0.064	−0.083	−0.104	−0.124
		0.006	0.006	0.009	0.014	0.020	0.027	0.041	0.053	0.067	0.078
86.65	−1.030	−0.000	−0.005	−0.009	−0.016	−0.023	−0.033	−0.043	−0.056	−0.071	−0.086
		0.004	0.004	0.006	0.006	0.007	0.009	0.011	0.012	0.015	0.021
154.3	−1.086	0.001	−0.000	−0.002	−0.004	−0.007	−0.010	−0.014	−0.018	−0.024	−0.027
		0.004	0.005	0.005	0.005	0.007	0.008	0.010	0.011	0.011	0.014
286.1	−1.069	−0.003	−0.004	−0.004	−0.004	−0.004	−0.004	−0.004	−0.005	−0.005	−0.007
		0.010	0.010	0.011	0.011	0.012	0.011	0.010	0.011	0.012	0.020

use Table II or Table III to calculate the shift in resistance of the sensor, then use the temperature dependent dimensionless sensitivity data from the calibration data of that particular sensor to calculate the equivalent shift in its apparent temperature.

Selected results from Tables II and III are plotted in Fig. 2 to show how the magnetoresistance depends on temperature and field. It should be kept in mind that thermometrically, small magnetoresistance at high temperatures can be as important as larger magnetoresistance at low temperatures due to the temperature dependence of the dimensionless sensitivity. (See also Fig. 6.)

B. Orientation dependence

Previous work on CGRTs[1] and other amorphous materials led us to expect that any sensor orientation effects would be small. Nevertheless, we did check some of the units with the film plane oriented so that the field vector lay in the plane of the film in dip experiments at 4.2 and 78 K. This was called the "coplanar" magnetoresistance. Two sensors were measured with the sample current parallel to the magnetic field vector to reveal the "parallel" magnetoresistance.

The results of the orientation dependence measurements are presented as the difference between the magnetoresistance offsets, expressed as percentages, measured in two ex-

TABLE III. Magnetoresistance of six Cernox™ sensors, 23–32 T. The values of S_T are the same as in Table II. The upper figures in each pair of rows are the mean values of the tabulated quantities, and the lower figures are the calculated standard deviations.

		$\Delta R/R$ (%) as a function of T (kelvins) and B (teslas)			
T (K)	S_T	B = 23 T	26 T	29 T	32 T
2.03	−1.94	−10.66	−12.56	−14.55	−16.59
		1.02	1.31	1.83	2.37
2.58	−1.69	−5.70	−7.42	−9.21	−11.07
		1.46	1.87	2.32	2.82
2.98	−1.57	−3.50	−5.09	−6.82	−8.64
		1.72	2.15	2.61	3.11
3.46	−1.45	−1.69	−3.15	−4.77	−6.49
		1.91	2.36	2.83	3.29
4.24	−1.33	0.10	−1.12	−2.54	−4.12
		2.03	2.50	2.97	3.43
5.05	−1.24	1.05	0.12	−1.16	−2.57
		1.88	2.36	2.83	3.29
5.98	−1.16	1.68	0.90	−0.14	−1.28
		1.87	2.31	2.78	3.25
7.92	−1.046	1.79	1.38	0.72	−0.13
		1.55	1.97	2.40	2.83
10.38	−0.999	1.36	1.10	0.68	0.17
		1.19	1.53	1.89	2.26
15.01	−0.949	0.48	0.32	0.07	−0.27
		0.77	0.99	1.23	1.48
20.31	−0.939	−0.05	−0.19	−0.39	−0.66
		0.50	0.66	0.81	0.98
30.10	−0.953	−0.35	−0.49	−0.64	−0.83
		0.27	0.34	0.42	0.51
50.07	−0.989	−0.32	−0.41	−0.51	−0.63
		0.10	0.13	0.16	0.19
77.8	−1.021	−0.21	−0.27	−0.34	−0.41
		0.05	0.06	0.07	0.09

perimental runs. The differences were either (1) perpendicular minus coplanar magnetoresistance offset of canister packaged sensors, (2) perpendicular minus parallel magnetoresistance offset of hermetically packaged sensors, or (3) perpendicular minus perpendicular magnetoresistance offset of the single canister packaged "control" sensor (serial number X01185). For case (3), the first perpendicular magnetoresistance data for the control sensor were recorded when the other sensors were also perpendicular; the second perpendicular magnetoresistance data were recorded when the other sensors were coplanar or parallel with the field.

The solid lines in Fig. 3 show that there was no significant orientation effect at 78 K, since the effect was nearly the same as that observed in the control sensor represented by the dashed lines. There are three dashed lines because three sets of perpendicular magnetoresistance data were used.

The situation at 4.2 K (Fig. 4) is more complex than at 78 K. Some CXRTs have larger positive magnetoresistance

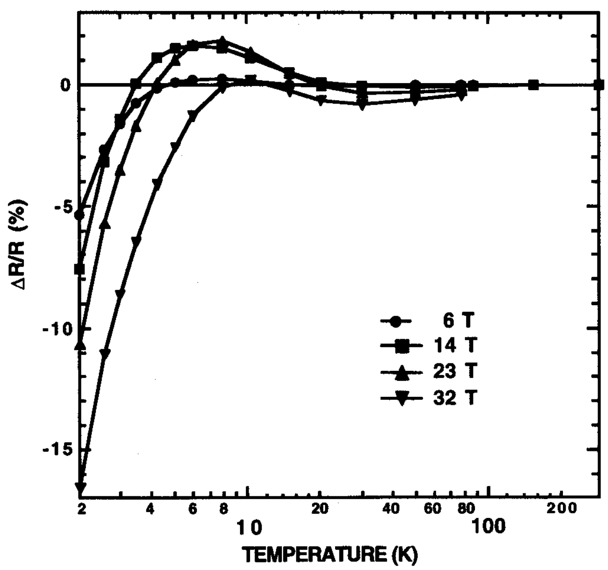

FIG. 2. Average perpendicular magnetoresistance vs temperature at selected fields.

in the perpendicular orientation than they do when coplanar or parallel; others have slightly smaller. At 20 T, the change in $\Delta R/R$ ranges from about −0.3% to +0.7% in resistance (−0.2% to +0.5% in temperature). Comparing these values with the mean perpendicular magnetoresistance values at 20 T from Table II reveals that changing the orientation of a CXRT can, in some cases, change the magnetoresistance by a large factor at low temperatures.

C. Discussion

The conclusions concerning the use of low-temperature thermometers in high magnetic fields that were drawn in

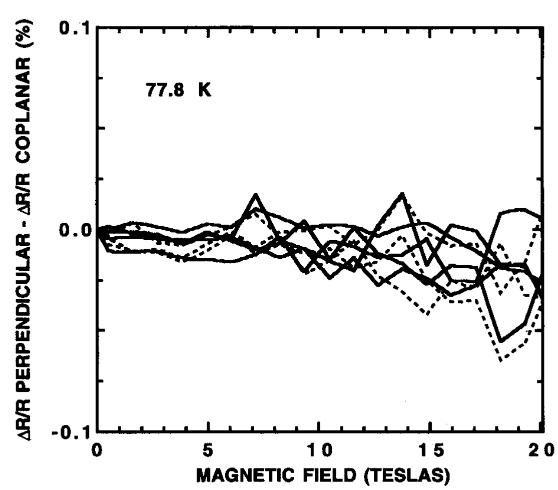

FIG. 3. Effect of sensor orientation on the magnetic field dependence of Cernox™ sensors at 78 K. The coplanar or parallel magnetoresistance offset of each sensor was subtracted from its perpendicular magnetoresistance offset. The dashed lines show the uncertainty in the data due to temperature drift and measurement noise as revealed by comparing perpendicular magnetoresistance data from a single control sensor taken when all the other sensors were in a parallel or coplanar orientation with data from the same sensor when other sensors were oriented perpendicular to the field.

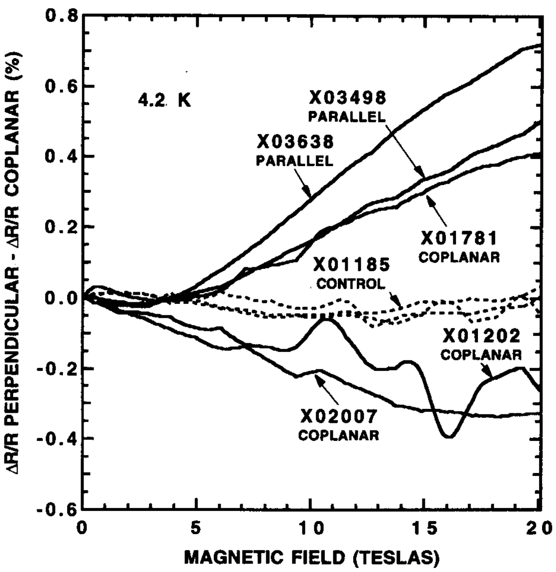

FIG. 4. Effect of sensor orientation on the magnetic field dependence of Cernox™ sensors at 4.2 K. The coplanar or parallel magnetoresistance offset of each sensor was subtracted from its perpendicular magnetoresistance offset. The dashed lines show the uncertainty in the data due to temperature drift and measurement noise as revealed by comparing perpendicular magnetoresistance data from a single control sensor taken when all the other sensors were in a parallel or coplanar orientation with data from the same sensor when other sensors were oriented perpendicular to the field.

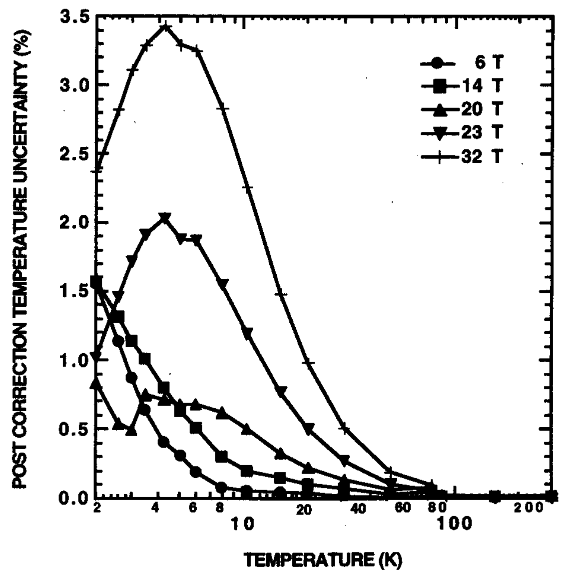

FIG. 5. Postcorrection temperature uncertainty vs temperature for Cernox™ sensors (see the text).

earlier work on CGRTs[1] have been updated in a recent review.[3] We can now answer one of the questions raised in that review concerning Cernox™ zirconium oxynitride sensors by comparing the uncertainty in the temperature following correction of the resistance value using Table II or Table III. The "postcorrection temperature uncertainty" is defined here as the calculated standard deviation about the mean values of $\Delta R/R$ (from Table II or Table III) divided by S_T. The resulting values for selected fields for the "typical" sensor whose S_T values are listed in Tables II and III, are shown in Fig. 5. The postcorrection temperature uncertainty determined in the measurements on nine CXRT sensors to 20 T is within 20% of the postcorrection temperature uncertainty possible with CGRTs.[1] Therefore we conclude that CXRTs are indeed a satisfactory alternative to CGRTs in fields to 19 T. The postcorrection temperature uncertainties of the CXRTs measured at fields over 20 T with only six sensors in the set studied are quite a bit higher than those at lower fields, primarily because the differences in $\Delta R/R$ behavior from one sensor to another become larger at the higher fields (see Table III and Fig. 5). Examples of the postcorrection temperature uncertainties shown in Fig. 5, converted from percentages to temperatures, are 22 mK at 4.2 K, 12 mK at 20 K, and 15 mK at 78 K for $B=10$ T; 22 mK at 4.2 K, 50 mK at 20 K, and 60 mK at 78 K for $B=20$ T; and 100 mK at 4.2 K, 170 mK at 20 K, and 60 mK at 78 K for $B=30$ T.

Other comparisons between the two thermometers favor the CXRTs. They are more robust. Their small chip size and the fact that they are sputtered films and do not need to be in strain-free mounts lead to ease of packaging, ease of mounting, better thermal contact to the outside world, and faster response times. The magnitude of their $\Delta T/T$, the uncorrected temperature error, is smaller than other sensors at most temperatures and fields (see Fig. 6 for a comparison with CGRTs and platinum resistance thermometers). The smaller deviations should lead to better control stability as the magnetic field is swept. And finally, the uncorrected temperature errors in the range from liquid nitrogen to room temperature are small enough (less than platinum resistance thermometers or CGRTs) that many users will not bother correcting them. Many users may choose to ignore the magnetoresistance errors at temperatures below 78 K; it depends on the application.

Cernox™ resistance thermometers are commercially available, can be supplied with a calibration over the entire 1.4–325 K range covered by this study, and are usable over that entire range. The correctabilities appear to apply to off-

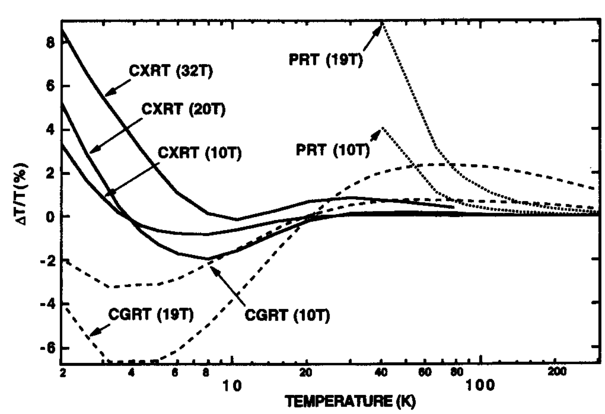

FIG. 6. Comparison of temperature errors due to magnetoresistance for carbon-glass and platinum sensors at $B=10$ and 19 T with Cernox™ sensors at 10, 20, and 32 T. $(\Delta T/T)=(\Delta R/R)/S_T$. Data are from Tables II and III of this work, Table II of Ref. 1, and Table II of Ref. 2.

the-shelf sensors with dimensionless sensitivities at 4.2 K in the range of -0.74 to -1.9, though limiting the range to -1.2 to -1.9 is recommended. The CXRT's disadvantages include a long term, zero-field calibration reproducibility that is still not proven, and a nonzero magnetoresistance that makes it inferior to the capacitance thermometer in certain situations, as are all resistance temperature sensors.

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