Appendix B: Sensor Characteristics

Types of temperature sensors

Any temperature dependent parameter can be used as a sensor if it fits the requirements of the given application. These parameters include resistance, forward voltage (diodes), thermal EMFs, capacitance, expansion/contraction of various materials, magnetic properties, noise properties, nuclear orientation properties, etc. The two most commonly used parameters in cryogenic thermometers are voltage (diodes) and resistance. There are distinct reasons for choosing diode thermometry or resistance thermometry.

Diodes

A diode temperature sensor is the general name for a class of semiconductor temperature sensors. They are based on the temperature dependence of the forward voltage drop across a p-n junction. The voltage change with temperature depends on the material. The most common is silicon, but gallium arsenide and gallium aluminum arsenide are also used.

Silicon diodes can be used from 1.4 K to 500 K. From 25 K to 500 K, a silicon diode has a nearly constant sensitivity of 2.3 mV/K. Below 25 K the sensitivity increases and is nonlinear. The temperature response curve is shown in Figure 1. Diode temperature sensors from Lake Shore (DT-670 Series) typically are mounted in a special semiconductor package (SD package). The semiconductor packaging is robust and allows for solder mounting for probes and circuits and easy installation and handling.

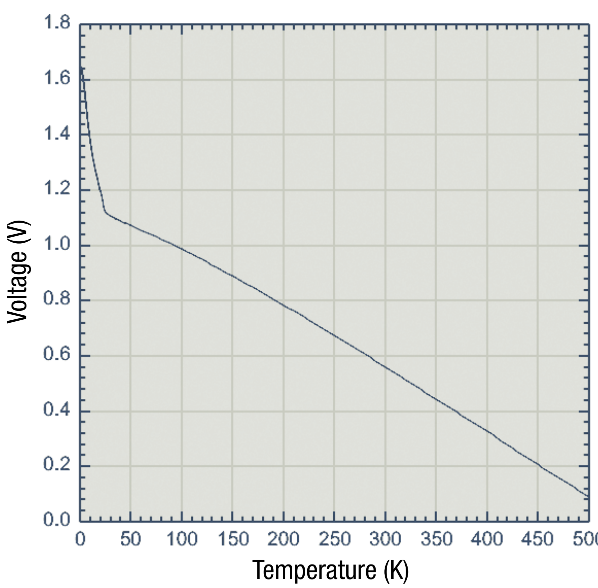


Figure 1 – Curve DT-670

Silicon diode sensors are typically excited with a constant 10 µA current. The output signal is fairly large: 0.5 V at room temperature and 1 V at 77 K. This can be compared to platinum where a 100 Ω PRT with a 1 mA excitation has only a 100 mV signal at 273 K. The straightforward diode thermometry instrumentation is shown in Figure 2.

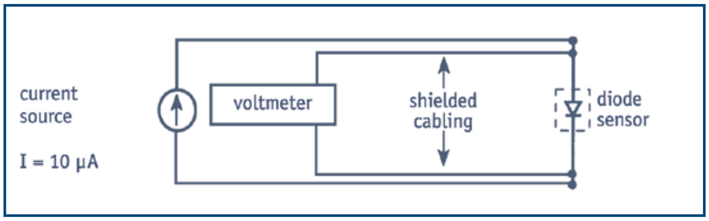


Figure 2 – Typical diode sensor instrumentation schematic

An important feature of silicon diodes is their interchange-ability. Silicon diodes from a particular manufacturer are interchangeable, or curve-matched over their whole range. This is typically defined in terms of tolerance bands about a standard voltage-temperature response curve. They are classified into different tolerance bands with the best accuracy being about ±0.25 K from 2 K to 100 K and ±0.3 K from 100 K to 300 K.

The large temperature range, nearly linear sensitivity, large signal and simple instrumentation make the diode useful for applications that require a better accuracy than thermocouples. Also, because of the large signal, a diode can be used in a two-lead measurement with little lead resistance error. AC noise-induced temperature errors, to which resistors are immune (aside from heating effects), can be prevalent in diodes.

Resistors

Temperature sensors based on the changing resistance with temperature can be classified as positive temperature coefficient (PTC) or negative temperature coefficient (NTC). Platinum RTDs are the best example of PTC resistance sensors. Other PTC RTDs include rhodium-iron, nickel, and copper RTDs. Figure 3 shows a typical resistance sensor instrumentation schematic.

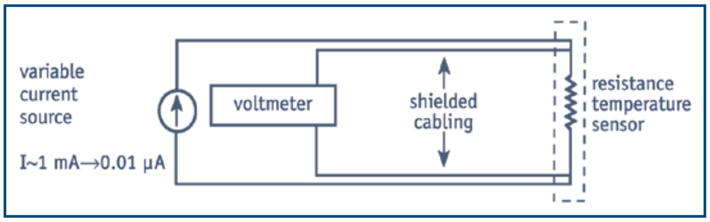


Figure 3 – Typical resistance sensor instrumentation schematic

A PTC RTD is typically metallic (platinum) and has a fairly linear temperature-resistance response. NTC RTDs are semiconductors or semi-metals (doped germanium, Cernox™). They have extremely nonlinear response curves, but are much more sensitive to temperature change.

Positive temperature coefficient (PTC) RTDs—The most common type of PTC RTD is platinum. Platinum RTDs are the industry standard due to their accuracy and reproducibility over a wide range of temperatures, as well as their interchangeability. Measurements in the range from -258 °C to 600 °C are routinely made with a high degree of accuracy using platinum RTDs. Industrial-grade platinum RTDs are wire-wound devices that are encapsulated in glass or ceramic, making them durable for general-purpose use.

Platinum RTDs follow a standard response curve to within defined tolerances (IEC 751). The industry standard for class B accuracy is specified as ±0.3 K and ±0.75% variation in the specified 0.00385 K^{-1} temperature coefficient of resistance at 273 K. Below 70 K, a platinum RTD is still usable but requires an individual calibration.

Like all resistors, platinum RTDs can be measured by current excitation or voltage measurement. Common configurations are two-, three-, and four-lead measurements. Two-lead measurements do not correct for lead resistance, so therefore can only be used in applications where the sensor is close to a temperature transmitter. Because their resistance change with temperature is linear over a wide range, a single current excitation (1 mA) can be used for the whole range.

Negative temperature coefficient (NTC) RTDs—NTC resistors are normally semiconductors with a very strong temperature dependence of resistance, which decreases with increasing temperature. It is not uncommon for the resistance to change five orders of magnitude over their useful temperature range. The three most common are germanium, Cernox™, and ruthenium oxide (Rox™) RTDs. Carbon-glass RTDs are still used, but they are generally being replaced by Cernox™ for nearly all applications.

Cernox™ is the trade name for zirconium oxy-nitride manufactured by Lake Shore Cryotronics, Inc. It is a sputter-deposited thin film resistor. Cernox shows good temperature sensitivity over a wider range (0.1 K to 420 K) and is highly resistant to magnetic field-induced errors and ionizing radiation. Cernox can be packaged in the same robust hermetically sealed SD package (Figure 4) that is used for diode temperature sensors. This makes Cernox more robust than other NTC RTDs.

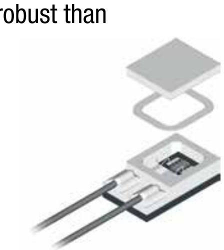


Figure 4 – CX-SD

Germanium and carbon-glass (Figures 5 and 6) have very large sensitivities, but more narrow operating ranges than Cernox. Germanium is very stable and is recognized as a secondary standard for T < 30 K. Both sensors are piezoresistive, so the sensing element must be mounted in a strain-free package, which provides a very weak thermal link to their surroundings. Both sensors are sealed in a helium atmosphere, but at lower temperatures the pressure is very low and the gas eventually liquefies, reducing the thermal contact. The requirement of strain-free mounting also results in a very fragile sensor. Dropping a sensor from a height of a few centimeters can cause shifts in the calibration.

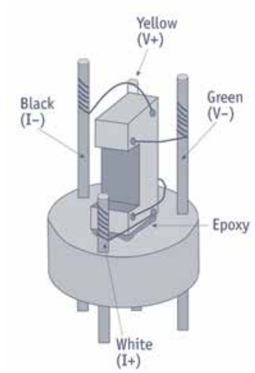


Figure 5 – Typical germanium packaging

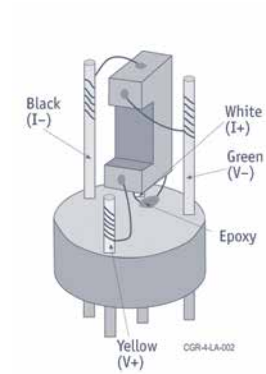


Figure 6 – Typical carbon-glass packaging

Ruthenium oxide is a generic name for a class of bismuth ruthenate thick-film resistors. They are epoxied to a BeO header, mounted, and sealed in gold-plated copper AA canisters. Unlike other NTC RTDs, Ruthenium oxide resistors are interchangeable and follow a standard curve. They can be used to below 50 mK and up to 40 K. Their sensitivity is negligible for T > 40 K.

For NTC RTD temperature sensors, up to 70% of the thermal connection to the sensor is through the leads. The large resistance change coupled with thermal considerations results in a requirement for a variable current source for measurement in which the current must be varied over several orders of magnitude (i.e., from about <0.01 µA to 1 mA or above) as well as a voltmeter capable of measuring voltages near 1 mV.

Capacitors

Capacitors are also used for low temperatures, but usually not for temperature measurement. Capacitance temperature sensors have the advantage of being insensitive to magnetic fields, but they commonly experience calibration shifts after thermal cycling and the $SrTiO_3$ capacitors have been known to drift over time while at low temperatures. Phase shifts in the ferroelectric materials are probably the cause of the thermal cycling shifts. The time response of capacitance sensors is usually limited by the physical size and low thermal diffusivity of the dielectric material. The capacitance is measured by an AC technique.

Thermocouples

Thermocouples are only useful where low mass or differential temperature measurements are the main consideration. They must be calibrated in-situ because the entire length of the wire contributes to the output voltage if it traverses a temperature gradient. Errors of 5 K to 10 K can easily occur.

Sensor selection

The most important question to ask when selecting a temperature sensor and instrumentation system is "What needs to be measured?" A simple question, but it can be surprisingly easy to answer incorrectly. Some processes need extremely high resolution over a narrow temperature range. Other systems need only a gross estimate of the temperature but over a very wide range.

Design requirements dictate the choice of temperature sensor and instrumentation. Not all applications require the same choice. Even within an application, different temperature sensors can be required. Selecting the appropriate sensor requires prioritizing the most important design attributes. Some attributes are not exclusive to others: The most stable sensors also have a very slow response rate and can be expensive, while sensors with the highest sensitivity have the smallest range.

Design requirements can be classified into four categories:

Quality of measurement—This concerns measurement uncertainty, resolution, repeatability, and stability.

Experimental design—This is related to constraints due to the experiment (or cryogenic system). It concerns the physical size of the sensors, temperature range of operation, and power dissipation.

Environmental constraints—These are effects due to external conditions such as magnetic fields or ionizing radiation. Other external constraints would be vibration or ultra high vacuum.

Utility requirements—These are primarily requirements for cost, ease of use, installation, packaging, and long-term reliability.

Quality measures

Accuracy versus uncertainty

The term "accuracy" has been almost universally used in literature when presenting specifications, and is often used interchangeably with uncertainty. However, from a strict metrology viewpoint, a distinction does exist between accuracy and uncertainty. Accuracy refers to the closeness of agreement between the measurement and the true value of the measure quantity. Accuracy is a qualitative concept and should not have numbers associated with it. This can be understood since, in practice, one does not have a priori knowledge of the true value of the measured quantity. What one knows is the measured value and its uncertainty, i.e., the range of values which contain the true value of the measured quantity. The uncertainty is a quantitative result and the number typically presented in specifications.

In any proper measurement, an estimate of the measurement uncertainty should be given with the results of the measurement. There are often many sources that contribute uncertainties in a given measurement, and rigorous mathematical methods exist for combining the individual uncertainties into a total uncertainty for the measurement. Temperature sensors, installation, environment, instrumentation, thermal cycling, and thermal EMFs can all contribute to the measurement uncertainty.

A sensor calibration is a method to assign voltage or resistance measurements to a defined temperature scale (i.e., ITS-90 or PLTS-2000). The level of confidence at which this can be done (measuring voltage or resistance AND transferring those values to a defined temperature) is defined by the uncertainty of the calibration.

The uncertainty of the Lake Shore calibration is only one component in a customer measurement system.

It is possible to degrade this accuracy specification by as much as one or two orders of magnitude with improper installation and/or poor shielding and measurement techniques.

Repeatability (of the measurement)

The exact definition of repeatability is the closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement (repeatable conditions).

Repeatability is a measure of how well a sensor repeats its measurement under the same conditions. This is often thought of as measurement performed over a period of time (seconds, minutes, hours) at the same temperature. This property is often called precision or stability of the measurement. This value is primarily an instrumentation specification. The sensors themselves are very stable under successive measurements. The stability of the instrument used to measure the sensor needs to be included.

Reproducibility

The definition of reproducibility is the closeness of agreement between the results of the measurements of the same measurand carried out under changed conditions of measurements. Often the changed conditions are thermal cycling or mounting (or unmounting) of the sensors. Temperature sensors are complex combinations of various materials bonded together. Aging, thermal cycling, mechanical shock from handling, etc. all affect the reproducibility.

Lake Shore quantifies the reproducibility under thermal cycling in two manners:

Short-term reproducibility: Changes in response values under repeated, successive cycles from ambient to liquid helium (4.2 K).

Long-term stability: Changes in response after 200 thermal shocks in LN_2 (77 K). Calibrations are performed prior to and after the thermal cycles.

Actual long-term stability for a specific sensor depends on the treatment of the sensor in terms of handling and thermal cycling. A single mechanical shock can cause an immediate calibration shift.

Users should include the short-term reproducibility value in their total uncertainty estimates.

Sensitivity and resolution

Sensitivity can be presented in a variety of ways. Typically, it is given in terms of the signal sensitivity, which is the change in a measured parameter per change in temperature (Ω/K or V/K). These sensitivities can be a very strong function of temperature. Diodes have sensitivities that range from 2 mV/K to 180 mV/K. Resistor sensitivities can range from less than 0.001 Ω/K to 1,000,000 Ω/K, depending upon the device type and temperature.

For resistors, the above signal sensitivity (dR/dT) is geometry dependent (i.e., dR/dT scales directly with R), consequently, very often this sensitivity is normalized by dividing by the measured resistance to give a sensitivity, S_T, in change per kelvin

$$S_T = (1/R)(dR/dT), \qquad \textit{Eqn. 1}$$

where T is the temperature in kelvin and R is the resistance in ohms. This is a common method to express the sensitivity of metal resistors like platinum RTDs.

When comparing different resistance sensors, another useful materials parameter to consider is the dimensionless sensitivity. The dimensionless sensitivity S_D for a resistor is a material-specific parameter given by

$$S_D = (T/R)^*(dR/dT) = d(\ln R)/d(\ln T) \qquad \textit{Eqn. 2}$$

Equivalent definitions are made for diodes with resistance replaced by forward voltage and for capacitors with resistance replaced by capacitance. S_D is also the slope of the resistance versus temperature on a log-log plot, normally used to illustrate resistance versus temperature for negative temperature resistance sensors since their resistance varies by many orders of magnitude. S_D ranges from 0.2 to 6 for most common cryogenic temperature sensors, depending on temperature and sensor type.

Temperature resolution is the smallest temperature difference that can be determined by your measurement system and sensor choice. It is a combination of sensor sensitivity and instrument resolution (ΔR). It can be expressed as

$$\Delta T = \Delta R /(dR/dT) \qquad \textit{Eqn. 3}$$
(or as a ratio $\Delta T/T = (\Delta R/R)/S_D$)

Instrument manufacturers will either express the resolution of the measurement as fraction of full scale (i.e., 1 part per million) or as an absolute ΔR (i.e., 1 Ω for 10,000 Ω scale). Do not confuse temperature resolution with display resolution; actual temperature resolution can be greater or less than the digital display resolution.

Experimental design

Range of use

Two factors limit the useful range of a sensor. First, the physical phenomena responsible for the temperature dependence of the property being measured must occur at a measurable level in both absolute signal and sensitivity to temperature change. Second, the materials used in construction of the temperature sensor must be appropriate to the temperature range of use. Materials such as epoxies, solders, and insulators that are very useful at low temperatures can break down at higher temperatures. Exposure to extreme temperatures (either high or low) can induce strains in the sensor due to changes in the packaging materials or in the leads; the resulting strain can cause a shift in the low temperature calibration for that sensor.

Physical size, construction, and thermal response times

As a general rule, larger sensors will be more stable, but they may have a longer thermal response time and may not fit into many experimental schemes. This can be somewhat deceptive, however, because the actual thermal response time depends integrally upon the physical construction of the sensor (i.e., the temperature sensing element) and its associated packaging. Strain-free mounting of sensor elements inside the package necessarily makes for poor thermal connection and longer thermal response times. The choice of package materials can also have a great effect on thermal response times at low temperatures.

Thermal response times are determined by physical construction material and mass of the temperature-sensing element. Strain-free mounted sensors tend to have longer thermal response times. Diode sensors that are mounted directly on a sapphire substrate will be in very good thermal contact with the surroundings and hence have short thermal response times. Thermal response times for various sensors are given in Table 1. The values listed are the 1/e response times.

Table 1—Thermal response times

	4.2 K	77 K	273 K
DT-470-SD	<10 ms	100 ms	200 ms
DT-420	<10 ms	50 ms	NA
CX-XXXX-BC	1.5 ms	50 ms	135 ms
CX-XXXX-SD	15 ms	250 ms	0.8 s
CX-XXXX-AA	0.4 s	1 s	1 s
GR-200A-1000	200 ms	3 s	NA
CGR-1-1000	1 s	1.5 s	NA
PT-102	NA	1.75 s	12.5 s
PT-111	NA	2.5 s	20 s
TG-120-PL	100 ms	250 ms	3 s
RF-100-AA	0.8 s	3.6 s	14.5 s
RF-100-BC	2 ms	12 ms	35 ms

Power dissipation

Diode, resistance, and capacitance temperature sensors must all be energized electrically to generate a signal for measurement. The power dissipated within the temperature sensor must be appropriate for the temperature being measured; the joule heating within the temperature sensor causes an incremental temperature rise within the sensor element itself (self-heating). Consequently, this temperature rise must be kept negligible compared to the temperature of interest.

For diodes, a fixed excitation current of 10 µA is a compromise between power dissipation and noise immunity. The power dissipated is the product of voltage times current. Since the voltage increases with decreasing temperature, power also increases, resulting in a practical lower temperature limit for diode thermometers of slightly above 1 K.

Resistors, on the other hand, have a linear I-V relationship that allows (at a fixed temperature) the measurement of resistance at many different currents and voltages. Since positive temperature coefficient resistance temperature sensors vary relatively linearly with temperature, they can normally be measured by utilizing a fixed current chosen such that self-heating over the useful temperature range is minimized.

In the case of negative temperature coefficient resistance temperature sensors such as Cernox™ or germanium RTDs, resistance can vary by as much as five orders of magnitude. To keep the joule heating low, their resistance must be measured either at a fixed voltage or with a variable current selected to keep the resulting measured voltage between 1 mV and 15 mV.

Table 2 gives some typical values of appropriate power levels to use with various temperature sensors in various ranges. These power dissipation levels should keep the temperature rise below 1 mK.

Table 2—Power (W)

	Cernox™, carbon-glass, germanium, Rox™	Platinum, rhodium-iron
0.02 K	10^{-14}	—
0.1 K	10^{-10}	—
1 K	10^{-9}	10^{-7}*
2 K to 10 K	10^{-8}	10^{-6}*
10 K to 100 K	10^{-7} to 10^{-6}	10^{-5}
273 K	10^{-6} (CGR, CX)	3×10^{-5}

**Rhodium-iron only*

Environmental

Usefulness in magnetic fields

Probably the most common harsh environment that temperature sensors are exposed to is a magnetic field. Magnetic fields cause reversible calibration shifts, which yield false temperature measurements. The shift is not permanent and sensors will return to their zero-field calibration when the field is removed.

The usefulness of resistance temperature sensors in magnetic fields depends entirely on the particular resistance temperature detector (RTD) chosen. The Lake Shore Cernox™ thin-film resistance sensors are the recommended choice for use in magnetic fields. The Cernox™ sensors are offered in a variety of packages and have a wider temperature range than carbon-glass. Ruthenium oxide RTDs are a good choice for temperature below 1 K and down to 50 mK or lower. Due to their strong magnetoresistance and associated orientation effect, germanium sensors are of little use in magnetic fields.

Depending on the desired accuracy, silicon diodes can be used effectively in certain temperature ranges (<0.5% error above 60 K in 1 T fields). However, special care must be taken in mounting the diode to ensure that the junction is perpendicular to field, i.e., current flow is parallel to the magnetic field. Diodes are strongly orientation dependent.

Capacitors are excellent for use in magnetic field environments as control sensors. They can be used in conjunction with another type of sensor (Cernox™, carbon-glass, germanium, etc.) to control temperature. The temperature is set using the other sensor before the field is turned on. Control is then accomplished with the capacitor. Table 3 (page 162) shows magnetic field dependence for some Lake Shore sensors.

Usefulness in radiation

Ionizing radiation refers to a broad class of energetic particles and waves. The effects of radiation can produce temporary or permanent calibration shifts. The exposure can be measured using standard dosimetry techniques, but the actual absorbed dose will vary depending on the material. Due to extensive work performed on the effects of radiation on biological tissue and Si semiconductor devices, the dose is often expressed either in tissue equivalent dose or dose Si, i.e., grays (1 gray = 100 rad).

The data for neutron radiation is more difficult to interpret than gamma radiation data because effects occur due to both the neutrons and the associated background gamma radiation. In both cases it is difficult to calculate or measure the actual absorbed dose. The actual absorbed dose depends on dose rates, energy of the radiation, exposure dose, material being irradiated, etc. Figures 7a to 7e (pages 163 to 164) show data for various sensors.

Usefulness in ultra high vacuum systems

The bakeout procedure performed in most ultra high vacuum systems can be damaging to the materials used in the construction of a temperature sensor. Even if the sensor withstands the high bakeout temperature, the sensor's calibration may shift. Without the bakeout, (and possibly with it) some materials in the sensor (Stycast®, for example) may interfere with the high vacuum by acting as a virtual leak. There can be a considerable outgassing from various types of epoxies and ceramics, and some of these materials would not survive the high temperature bake. With proper packaging, diodes, Cernox™, rhodium-iron, and platinum RTDs can be easily used in ultra high vacuum systems that require a high temperature bake out.

Specific factors to be aware of in an ultra high vacuum environment are:

- Check the compatibility of construction materials of the sensor with ultra high vacuum before using it in such an environment. This includes thermal grease, epoxies, and solders (e.g., Apiezon® N grease cannot be used in these systems due to vapor pressure).
- Solders may not be compatible. Welding may be required.
- Typical insulation used for cryogenic wire may be incompatible with high temperature bakeouts and ultra high vacuums due to thermal ratings and outgassing.

The Lake Shore SD package for diodes is considered UHV compatible. A special package exists for the Cernox™ sensor that uses spot welded platinum leads.

A useful website with more information on outgassing properties of materials is found at http://outgassing.nasa.gov.

Vibration (shock) environments

Subjecting a temperature sensor to vibrations can permanently shift the calibration, either slowly or catastrophically. Sensors such as germanium and carbon-glass are mounted in a strain-free manner, and mechanical shocks due to vibration will have the same effect on the sensor as dropping it. Other sensors including Cernox™ and silicon diodes, due to their physical construction and packaging are less susceptible to vibration-induced errors.

Flight qualified

For special applications, Lake Shore will test and qualify sensors to flight standards. Silicon diode and Cernox™ sensors, due to their characteristics, performance, construction, and packaging are ideally suited for many flight and large projects applications. Tests are performed to the required standards (for example MIL-STD-750 or MIL-STD-883). Some tests include burn-in lifetime tests, thermal shock, vibration, PIND, gross and fine leak (hermeticity), x-ray, and long and short-term stability.

Table 3—Typical magnetic field-dependent temperature errors ΔT/T (%) at B (magnetic induction)

		Magnetic flux density B				
	T(K)	2.5 T	8 T	14 T	19 T	Notes
Cernox™ 1050 (CX series)	2	1.3	3.1	3.9	5	Best sensor for use in magnetic field (T > 1 K)
	4.2	0.1	-0.15	-0.85	-0.8	
	10	0.04	-0.4	-1.1	-1.5	
	20	0.04	0.02	-0.16	-0.2	
	30	0.01	0.04	0.06	0.11	
	77	0.002	0.022	0.062	0.11	
	300	0.003	0.004	0.004	0.006	
Carbon-glass resistors (CGR series)	4.2	-0.5	-2.3	-4.9	-6.6	
	10	-0.2	-1.1	-2.6	-3.8	
	25	0.02	0.22	0.54	0.79	
	45	0.07	0.48	1.32	2.2	
	88	0.05	0.45	1.32	2.3	
	306	<0.01	0.22	0.62	1.1	
Rox™ 102A	2	-1.4	-7.9	-13	-17	Recommended for use over the 0.05 K to 40 K temperature range. Consistent behavior between devices in magnetic fields.
	3	-1.5	-7	-14	-18	
	4	-0.56	-6.7	-14	-18	
	8	-1.3	-6.1	-13	-21	
	16	-0.40	-3.4	-9.6	-16	
	23	-0.31	-2.2	-6.2	-11	
Rox™ 103A	2	0.58	1.5	2.2	2.6	Excellent for use in magnetic fields from 1.4 K to 40 K. Predictable behavior.
	3	0.44	1.1	1.7	2.0	
	4	0.27	0.95	1.4	1.7	
	8	0.11	0.49	0.71	0.80	
	16	0.018	0.076	0.089	0.040	
	23	0.0051	0.0058	-0.0060	-.0.095	
Rox™ 202A	2	-0.13	-2.2	-3.9	-5.2	Recommended for use over the 0.05 K to 40 K temperature range. Consistent behavior between devices in magnetic fields.
	3	0.18	-0.68	-2.7	-3.7	
	4	0.77	0.046	-1.8	-3.2	
	8	-0.023	0.16	-0.65	-3.0	
	16	0.03	0.16	-0.48	-1.5	
	23	-0.05	-0.08	-0.39	-0.92	
Platinum resistors (PT Series)	20	20	100	250	—	Recommended for use when T ≥ 40 K.
	40	0.5	3	6	8.8	
	87	0 .04	0.4	1	1.7	
	300	<0.01	0.02	0.07	0.13	
Rhodium-iron (RF Series)	4.2	11	40	—	—	Not recommended for use below 77 K in magnetic fields.
	40	1.5	12	30	47	
	87	0.2	1.5	4	6	
	300	<0.01	0.1	0.4	—	
Capacitance CS-501 Series		ΔT/T(%) <0.015 at 4.2 K and 18.7 T ΔT/T(%) <0.05 at 77 K and 305 K and 18.7 T				Recommended for control purposes. Monotonic in C vs. T to nearly room temperature.
Germanium resistors (GR Series)	2.0	-8	-60	—	—	Not recommended except at low B owing to large, orientation-dependent temperature effect.
	4.2	-5 to -20	-30 to -55	-60 to -75	—	
	10	-4 to -15	-25 to -60	-60 to -75	—	
	20	-3 to -20	-15 to -35	-50 to -80	—	
Chromel-AuFe (0.07%)	10	3	20	30	—	Data taken with entire thermocouple in field, cold junction at 4.2 K; errors in hot junction.
	45	1	5	7	—	
	100	0.1	0.8	—	—	
Type E thermocouples (chromel-constantan)	10	1	3	7	—	Useful when T ≥ 10 K. Refer to notes for Chromel-AuFe (0.07%).
	20	<1	2	4	—	
	455	<1	<1	2	—	

	T(K)	1 T	2 T	3 T	4 T	5 T	Notes
Silicon diodes Junction parallel to field (DT Series)	4.2	-200	-300	-350	-400	-500	Strongly orientation dependent.
	20	-10	-20	-25	-30	-40	
	40	-4	-6	-8	-10	-12	
	60	-0.5	-1	-2	-3	-3.5	
	80	<0.1	-0.5	-0.8	-1.1	-1.5	
	300	<0.1	<-0.1	<-0.1	<-0.1	<-0.1	
Silicon diodes Junction perpendicular to field (DT Series)	4.2	-8	-9	-11	-15	-20	Strongly orientation dependent.
	20	-4	-5	-5	-5	-10	
	40	-1.5	-3	-4	-5	-5.5	
	60	-0.5	-1	-2	-3	-3.5	
	80	-0.1	-0.3	-0.5	-0.6	-0.7	
	300	<0.1	0.2	0.5	0.6	0.6	
GaAlAs diodes (TG Series)	4.2	2.9	3.8	3.7	2.8	1	Shown with junction perpendicular (package base parallel) to applied field B. When junction is parallel to B, induced errors are typically less than or on the order of those shown.
	30	0.2	0.2	0.3	0.3	0.2	
	78	<0.1	<0.1	0.17	0.16	0.1	
	300	-0.1	<0.1	<0.1	<0.1	<0.1	

Figure 7a—Gamma rays

Temperature shift as a function of temperature due to 10,000 Gy gamma radiation dose from a Cs-137 source. Dose rate was 0.5 Gy/min with irradiation performed at 298 K.

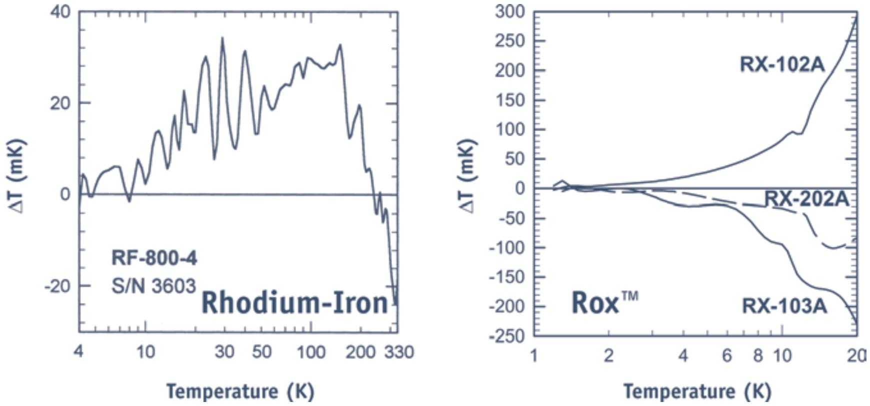
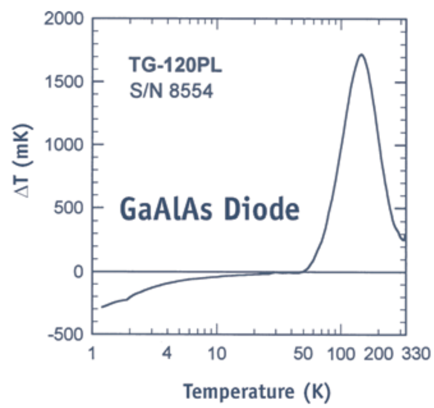


Figure 7b—Neutrons and gamma rays

Temperature shift as a function of temperature due to a 2.5 × 10^{12} neutron/cm^2 fluence from a nuclear pool reactor. The neutron flux was 3.75 × 10^7 neutron/cm^2/s with irradiation performed at 298 K (associated gamma ray dose of 29 Gy).



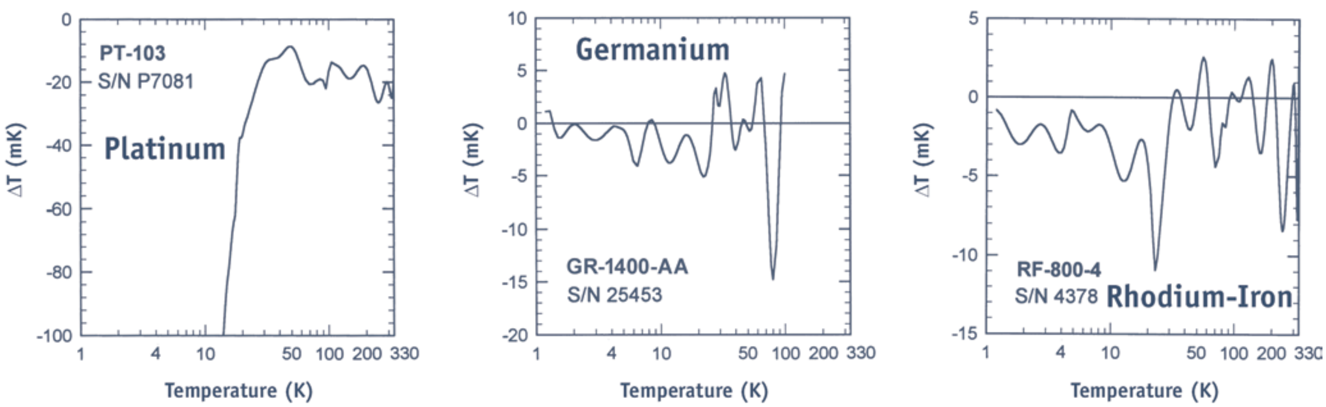


Figure 7c—Neutrons and gamma rays

Temperature shift as a function of temperature due to a 10^{14} neutron/cm^2 fluence from a nuclear pool reactor. The neutron flux was 2×10^{12} neutron/cm^2/s with irradiation performed at 298 K (associated gamma ray dose of 116 Gy).

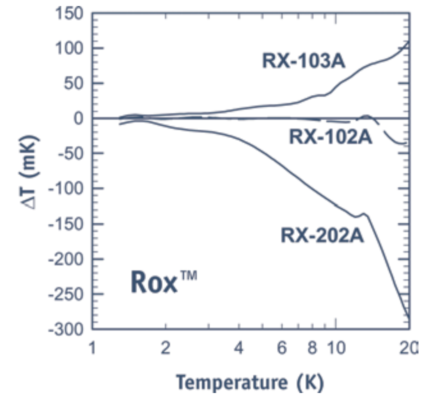


Figure 7d—Gamma rays

Temperature shift as a function of temperature due to 10,000 Gy gamma radiation dose from a Co-60 source. Dose rate was 40 Gy/min with irradiation performed at 4.2 K.

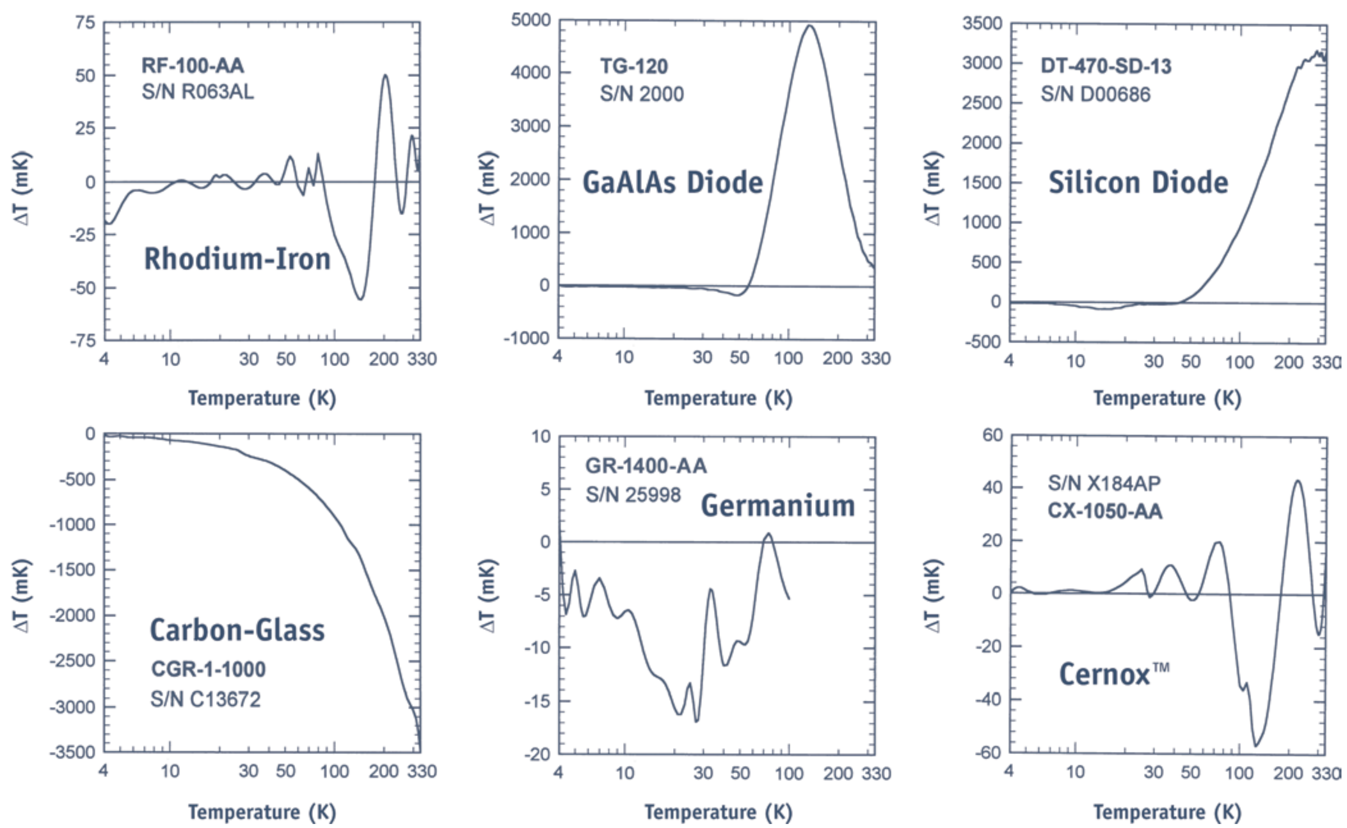
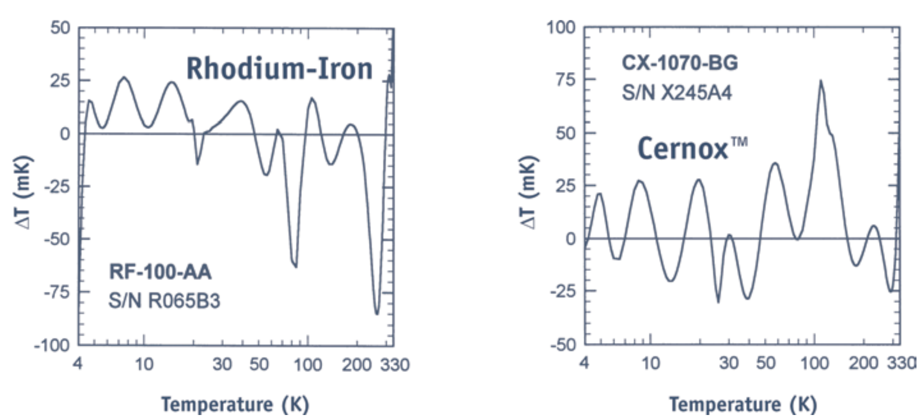


Figure 7e—Neutrons and gamma rays

Temperature shift as a function of temperature due to a 2×10^{12} neutron/cm^2 fluence from a nuclear pool reactor. The neutron flux was 7.5×10^7 neutron/cm^2/s with irradiation performed at 4.2 K (associated gamma ray dose of 23 Gy).



Utility

Interchangeability

It is very convenient and cost effective to have temperature sensors that match a standard curve, thus not requiring individual calibration. Such sensors are termed "interchangeable." In industry, interchangeable sensors make equipment design and manufacture simpler. Any monitoring equipment for those sensors can be identical. Time is saved in research settings since new calibrations do not have to be programmed into control and data acquisition equipment each time a new sensor is installed.

Some cryogenic temperature sensors exist at present which are interchangeable within a given tolerance band. Silicon diodes from Lake Shore are interchangeable. Series DT-670 diodes conform closely to a curve that Lake Shore calls Curve 670. The conformance is indicated by placing the diodes within tolerance bands. These sensors can be ordered by simply specifying a tolerance band. In this case, individual calibrations are not performed. If the greater accuracy is required, a calibration is necessary. Calibration can decrease the uncertainty by a factor of 10 or more. The DT-470 also follows a unique standard curve and is interchangeable with other DT-470s.

In addition to silicon diodes, platinum and ruthenium oxide RTDs both follow standard curves. Platinum RTDs match an industry standard curve (IEC 751) in terms of resistance versus temperature. Industrial platinum resistance temperature sensors are broken into Class B tolerances and Class A tolerances. Lake Shore offers only Class B sensors.

Ruthenium oxide RTD sensors also follow a standard curve. Like silicon diodes, this curve is unique to each manufacturer.

Signal size

For resistors, values lie between approximately 10 Ω and 100,000 Ω. Resistance measurements outside this range become more difficult to perform, especially at ultra-low temperatures. Keep in mind that for carbon-glass, Cernox™, and germanium sensors, there are several resistance ranges available to suit the appropriate temperature range(s). Because of their rapidly changing resistance and use at ultra-low temperature, it is necessary to use a small excitation current. The resulting voltage measurement can be in the nanovolt range in some cases. At these low voltages a variety of noise sources begin to affect the measurement.

Diode temperature sensors have a relatively large output (about 1 V) and a fixed current excitation of 10 µA. This allows for simple instrumentation compared to NTC RTDs like Cernox™.

Packaging

Sensors come in various packages and configurations. Apart from the size considerations discussed previously, there are practical considerations as well. A cylindrical package is obviously better suited for insertion into a cylindrical cavity than a flat or square-shaped package. Lake Shore offers a variety of sensor packages and mounting adaptors as well as probe assemblies. The most common package is the SD package. It is a robust and reliable hermetically sealed flat package. With a metallized and insulated bottom, the SD package can be indium soldered to the experimental surface. It can also be mechanically clamped as well as varnished or epoxied. The SD package can also be mounted into adaptor packages like the CU bobbin.

Many RTDs like germanium and Cernox™ are mounted in cylindrical AA canisters. This is a requirement for GRTs due to their strain-free mounting. Cernox™ is also available in a SD package.

Many cryogenic sensors can be packaged into custom probes and thermowells. Lake Shore has many standard probe configurations and can manufacture special customer designed probes for various applications.