A NEW CRYOGENIC DIODE THERMOMETER

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ABSTRACT

While the introduction of yet another cryogenic diode thermometer is not earth shattering, a new diode thermometer, the DT-600 series, recently introduced by Lake Shore Cryotronics, possesses three features that make it unique among commercial diode thermometers. First, these diodes have been probed at the chip level, allowing for the availability of a bare chip thermometer matching a standard curve – an important feature in situations where real estate is at a premium (IR detectors), or where in-situ calibration is difficult. Second, the thermometry industry has assumed that interchangeability should be best at low temperatures. Thus, good interchangeability at room temperatures implies a very good interchangeability at cryogenic temperature, resulting in a premium priced sensor. The DT-600 series diode thermometer is available in an interchangeability band comparable to platinum RTDs with the added advantage of interchangeability to 2 K. Third, and most important, the DT-600 series diode does not exhibit an instability in the I-V characteristic in the 8 K to 20 K temperature range that is observed in other commercial diode thermometer devices [1]. This paper presents performance characteristics for the DT-600 series diode thermometer along with a comparison of I-V curves for this device and other commercial diode thermometers exhibiting an I-V instability.

INTRODUCTION

The forward voltage drop across a silicon diode junction is a strong function of temperature, making it useful as a thermometer. Proper design of the diode can yield a high-signal, high sensitivity thermometer over the 1 K to 500 K temperature range. The use of silicon diodes for thermometry purposes has been studied for forty years [1-16]. Currently, at least four companies offer silicon diodes specifically for cryogenic thermometry use [17-20], and the use of common diodes/transistors manufactured by the electronics industry for thermometry is widespread (e.g. models 2N2222 and 1N4001-5).

Cryogenic diode thermometers possess significant advantages over other types of thermometers, especially resistive thermometer devices (RTDs). The instrumentation required for diode thermometry is usually cheaper than for RTDs. The manufacturing methods by which diodes are fabricated yield devices so uniform that a standard response curve for a particular model can be developed with tolerances as good as a tenth of a kelvin at low temperatures to a few tenths of a kelvin at room temperature, thus eliminating the need for expensive individual calibrations in many applications. Diode thermometers produce a high signal and high sensitivity over their entire useful temperature range. Packaging is typically simpler for diodes since they do not require the strain-free mounting required by many RTDs. Diode thermometers are also more robust and withstand thermal shocking much better than RTDs [21]. Cost, interchangeability, ease of use, and reliability have led to the widespread use of diode thermometry in cryopumps, liquid level detection and transfer, cryogenic coolers and refrigerators, focal plane arrays, and a host of smaller applications.

This paper details the advances made in silicon diode thermometry with the introduction of the DT-600 series by Lake Shore Cryotronics, Inc.

DATA

A complete description of the DT-600 series diode thermometer is not possible due to the proprietary nature of the diode design. Instead, this paper presents the operational characteristics of the diode – the more important aspect of the new diode from a user's point of view. All data reported were measured at the manufacturer's recommended excitation of 10 μA DC.

Response Curve

The forward voltage and sensitivity response curves for the DT-600 series diode thermometer are shown in Figure 1. They show the expected features of high sensitivity below 20 K (-15 to -38 mV/K), a sharp knee region in the 20 – 25 K temperature range, and a wide, nearly linear response range from 30 K – 500 K.

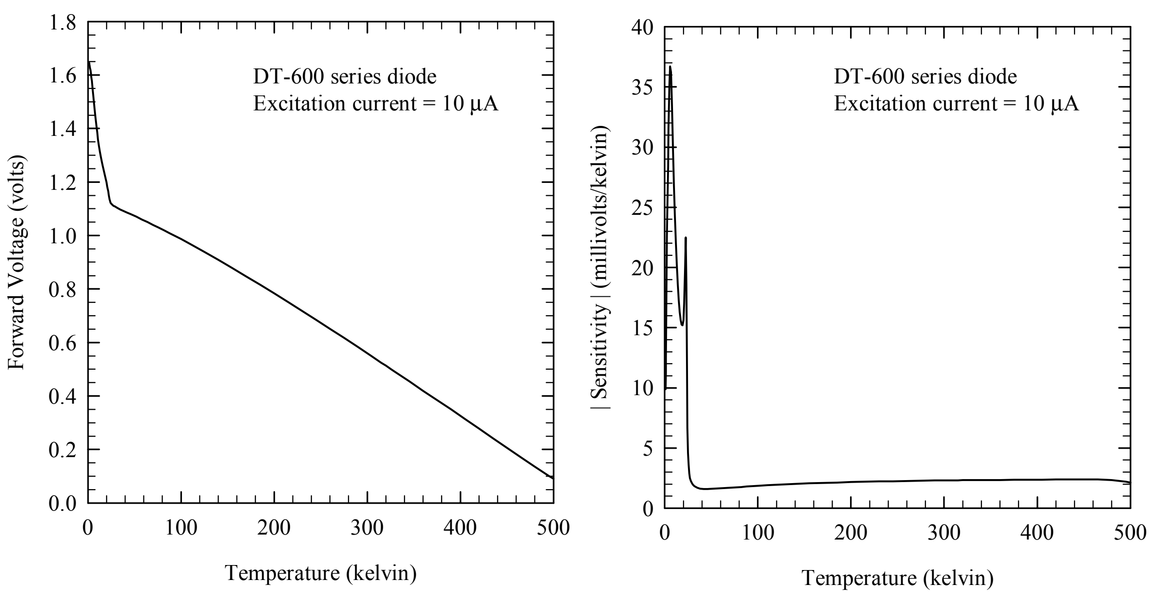

Figure 1. Forward voltage and sensitivity versus temperature for the model DT-600 series diode thermometer. Measurements taken at a constant 10 μA DC excitation.

Stability

An important characteristic for any thermometer is its short- and long-term stability. In both Figure 2a and 2b, an initial calibration forms the baseline. Figure 2a shows the short-term stability of the DT-600 series diode. Two consecutive calibrations were performed with no aging or thermal cycling between them. The increasing offset below 4 K is the result of the nonreproducibility of the mounting. Diodes are high dissipation devices, and the mounting is an integral part of the thermal system. At lower temperatures, changes in the thermal path are readily seen. The long-term stability of the DT-600 series diode is shown in Figure 2b. In this experiment, an initial calibration was performed, followed by 200 thermal shocks from room temperature to 77 K. A second calibration was then performed. As expected, the diode is very stable upon thermal cycling [21].

Interchangeability

The fabrication of the DT-600 series diode thermometer using standard semiconductor industry techniques results in a very precise process in which the resulting diodes are extremely uniform. This allows the diode thermometers to be grouped into a small number of tolerance bands about their typical response curve. The interchangeability can be as good as ± 0.5 K at room temperature to a ± 0.25 K at 4.2 K. The interchangeability is band dependent, and the more tightly matched to the standard curve the device is, the higher the premium paid by the user. Traditionally, the tightest tolerance was provided at the lowest temperature with the tolerance relaxed as temperature increased. Users working at 77.35 K (liquid nitrogen temperature) and higher were forced to pay a premium, since tight matching at higher temperatures implied even tighter matching at lower temperatures, resulting in a higher priced sensor. The commercially available tolerance/interchangeability bands for the DT-600 series are given in Table 1. It should be noted that the high power dissipation is a limiting factor at 2 K and below for interchangeability of all diode thermometers. At this temperature, diode thermometers dissipate about 16 μW compared to

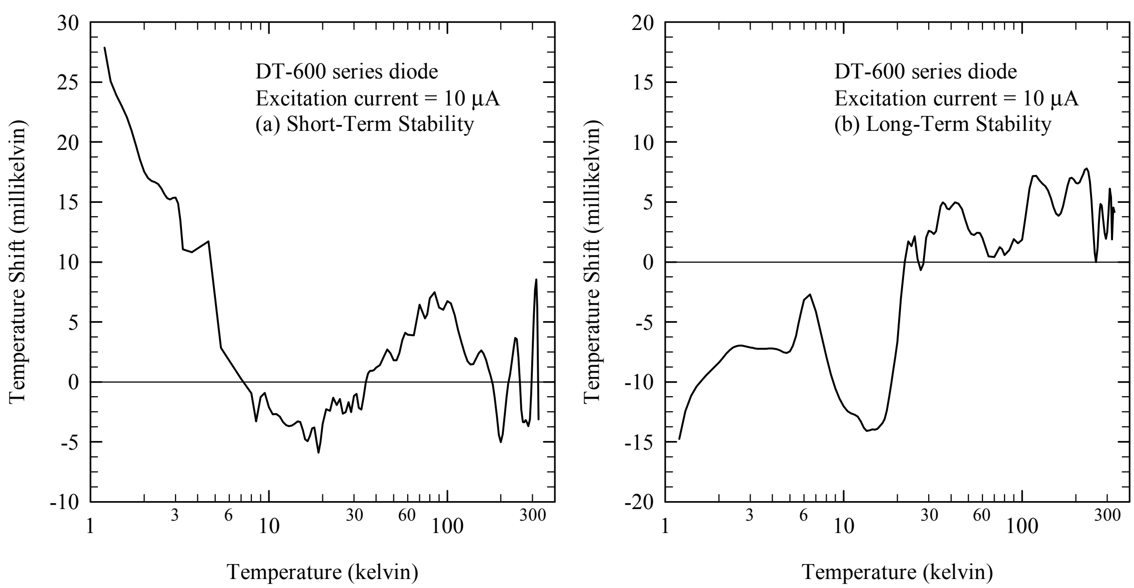

Figure 2. a) Typical short-term stability with data taken on two consecutive calibration runs and no dismounting of sensor. b) Typical long-term stability with 220 thermal shocks from room temperature to 77.35 K (liquid nitrogen temperature) between calibration runs.

Table 1. Tolerance bands for the DT-600 series diode thermometer.

Band	Temperature Tolerance at Temperature Range			
	2 K- 30 K	30 K- 100 K	100 K – 305 K	305 K – 500 K
A	± 0.25 K	± 0.25 K	± 0.50 K	± 0.50 K
B	± 0.50 K	± 0.50 K	±0.50 K	± 0.33% of T (1.01 – 1.65 K)
C	± 1.0 K	± 1.0 K	± 1.0 K	± 0.5% of T (1.53 – 2.50 K)
D (PRT Band)	± 1.5 K	± 0.25 K	± 0.30 K	± 0.1% of T (0.305 – 0.500 K)
E (Bare Chip Band)	± 1.0 K	± 0.25 K	± 0.25% of T (0.25 – 0.76 K)	± 0.25% of T ((0.76 – 1.25 K)
Calibration Accuracy	± 0.025 K	± 0.055 K	± 0.050 K	± 0.055 K

0.2 nW dissipated by resistive thermometers such as carbon glass RTDs or Cernox™ RTDs. Below 2 K, this high power dissipation can lead to self-heating as evidenced in liquid-to-vacuum calibration offsets and calibration offsets due to nonreproducibility of mounting. If better accuracy is needed beyond the interchangeability specifications, then the diodes can be individually calibrated, which increases their accuracy by a factor of ten or greater. The resulting calibration accuracies are listed in the last row of Table 1.

An advantage to the DT-600 series diode thermometer is that the devices were probed in wafer format at room temperature using an Alessi REL-4500 computer-controlled, automated prober with a temperature controlled chuck. Data generated from this process and samples taken from each wafer and calibrated allowed the diodes to be sorted into tolerance bands without further testing. These data also allowed the creation of a tolerance band equivalent to the interchangeability of PRTs in the 70 K to 500 K temperature range with the added advantage of a standard curve extension to 2 K.

Packaging and thermal time constant

The DT-600 series die chip is sold both as a bare chip and as a fully packaged device. As a bare chip, the overall dimensions are 0.41 mm wide x 0.43 mm long x 0.178 mm high, with a total mass of 73 µg. Estimates of the time constant yield a value of 1 µs at 4.2 K and 13 µs at 77 K [22]. The wafer probing and sampling method discussed above allow the bare chip to be sold matched to a standard curve, eliminating the need for an in-situ calibration. The availability of a characterized bare chip is extremely important in applications such as infrared focal plane arrays, where size and thermal mass must be minimized.

The standard package for this die chip is a flat, hermetically sealed package consisting of a sapphire base with alumina body and top. The overall dimensions are 1.9 mm wide x 3.2 mm long by 1.0 mm high, with a total mass of 37 mg. The diode chip is eutectically bonded to the metallized sapphire substrate in the cavity of the package. Gold wire bonds are made to finish the electrical connection, and the lid is soldered into place to form the hermetic seal. Feedthrough traces connect to the exterior of the cavity where kovar leads are spot welded. This package was specially designed for cryogenic diode thermometry, to provide excellent thermal connection between the diode and outside world. In this configuration, the thermal time constant was measured to be less than 10 ms at 4.2 K, less than 100 ms at 50 K, and less than 200 ms at 273 K.

Switching

Many diodes used for cryogenic thermometry exhibit an undesirable feature called switching, where an increase in current results in a decrease in forward voltage. This phenomenon is due to the presence of metastable states in the device, which is a result of the physical makeup of the device. In cryogenic diode thermometers, the switching is most likely seen in the 6 K to 15 K temperature range, although the range varies widely depending upon the exact model. In practice, switching can be observed by increasing the excitation current in small steps (e.g. 0.5 μA). The forward voltage drop should increase with increasing current, which it does until it reaches a switching current, at which point the voltage decreases sharply, arriving at a different I-V curve. Switching data for the Lake Shore DT-500 and DT-400 series were first reported in 1993 [15] along with data for industrial diode types 1N4001-6 and BYP 401. Figure 3 shows I-V curves at 9 K for a) the Lake Shore model DT-471-SD, b) a non-Lake Shore, commercially available diode thermometer, and c) the Lake Shore model DT-670-SD. Note the labeled switching points present in the DT-471-SD and the non-Lake Shore models.

Based on data collected during quality control testing of the DT-400 series, switching is observed in roughly 15% of the devices. Five non-Lake Shore devices purchased at various times, but from the same series, were tested, and all evidenced switching behavior. The data presented in Figure 3b was chosen to demonstrate that switching can occur both above and below the nominal 10 μA excitation current. Three of these five device switched only below 7 μA. Despite extensive testing of over 800 devices, no switching has been observed in the DT-600 diode thermometer series.

From a manufacturing point of view, the possibility of a device switching into metastable states requires the manufacturer to test each commercial device to ensure that switching, in fact, does not occur. Testing is both burdensome and lengthy due to the fact that the most likely temperature at which switching occurs is in the 6-15 K range. This temperature range can vary widely depending upon the design of the device.

However, it's important to put this phenomenon in perspective. The mere presence of switching does not render a particular diode device useless. First, the current at which the switching occurs is as important as the fact that it does occur. Switching that occurs at currents far from the manufacturer's recommended excitation current is unlikely to affect the diode's performance as a thermometer (Figure 3a). On the other hand, switching occurring close to the operating current can lead to erroneous results. This feature points out the importance of operating the device at the specified excitation. There are legitimate reasons for using a current other than the manufacturer's recommended excitation, such as needing a higher signal-to-noise ratio or needing to decrease power dissipation. However, operating at an excitation other than the recommended value may lead to erroneous results if the chosen current is near a switching current at the working temperature. Second, the spontaneous switching of a powered diode thermometer is extremely rare. The switching is most likely to occur when excitation cycled off and back on as in applications where several diode thermometers are scanned with a single set of instruments.

Radiation Environments

The physical design of most semiconductor devices includes a number of oxide layers used as insulators. When exposed to ionizing radiation, charging of the oxide layers combined with physical damage can dramatically alter the device's characteristics. Generally speaking, silicon diodes used for thermometry fall into this category and are not recommended for use in radiation environments. Small doses of radiation over long

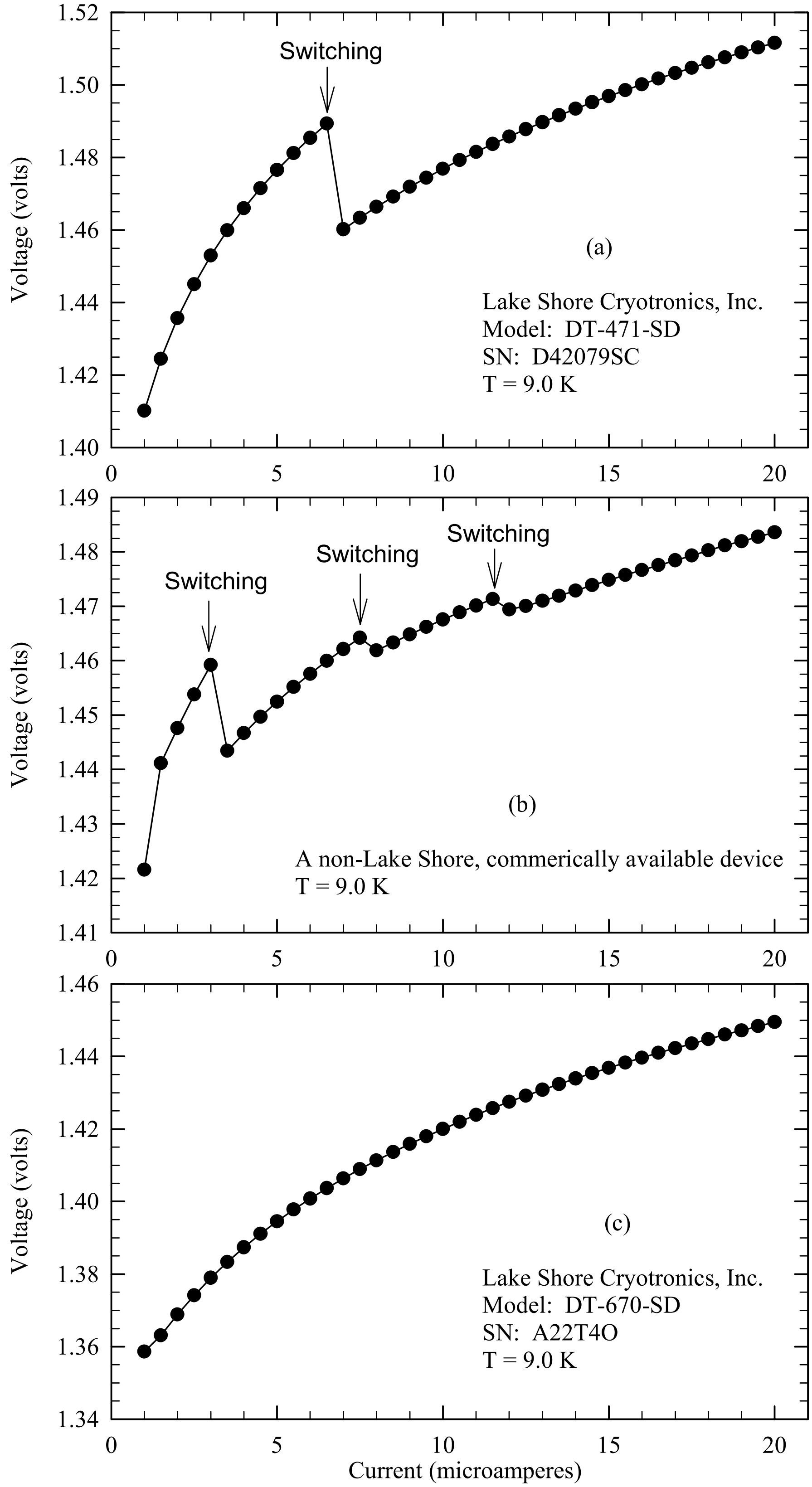

Figure 3. Voltage versus current for three models of cryogenic diode thermometers: a) Lake Shore model DT-471-SD, b) a non-Lake Shore, commercially available diode thermometer, and c) Lake Shore Cryotronics model DT-670-SD. Note the switching in the model DT-471-SD and the non-Lake Shore model.

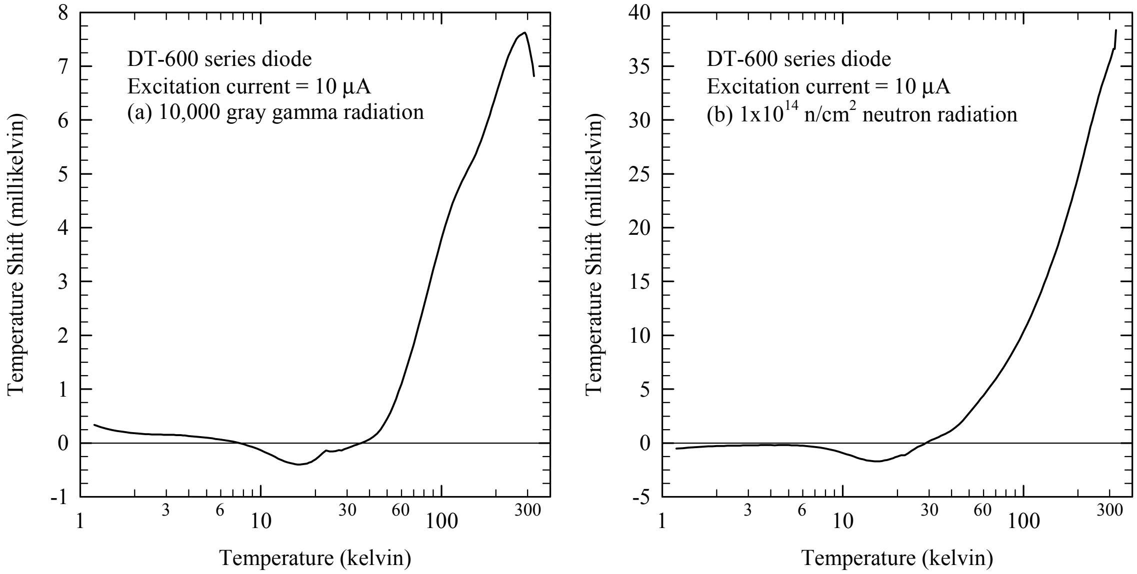

Figure 4. Radiation induced offsets in the DT-600 series. a) Gamma irradiated at room temperature to a total dose of 10,000 gray at a flux of 0.5 gray/minute by a cesium-137 source, b) Neutron irradiated at room temperature to a total fluence of $1x10^{12}$ neutrons/cm^2 in a pool reactor.

periods of time (e.g. space applications) may cause acceptable calibration shifts, but larger doses cause large calibration shifts as shown in Figure 4. Figure 4a shows the calibration shift due to a room temperature irradiation to 10,000 gray using a cesium-137 gamma radiation source with a 0.5 gray/s dose rate. Note that even at this high level, the induced offsets are still below 1 K for temperatures below 70 K. Figure 4b shows the calibration shift due to a room temperature irradiation to a fluence of $1x10^{14}$ neutrons/cm^2 using a pool reactor with a $2x10^{11}$ neutrons/cm^2/s flux.

Magnetic Field Environments

Silicon diodes are generally not used in magnetic fields due the large calibration shifts induced by those magnetic fields. These sensors behave as Hall Effect devices, where a magnetic field-induced voltage is created across the junction, leading to huge offsets which are both temperature dependent and orientation dependent. Typical magnetic field induced offsets measured at 4.2 K are listed for the DT-600 series diode in Table 2 for fields ranging from 0 to 5 tesla with the junction oriented both perpendicular to and parallel to the field.

Table 2. Model DT-600 series diode thermometers magnetic field-induced offsets at 4.2 K.

Junction Orientation	ΔT/T(%) at 4.2 K at Magnetic Field (tesla)						
	0.1	0.5	1	2	3	4	5
Junction Perpendicular to field	-4.7	-15	-16	-18	-20	-23	-26
Junction parallel to field	-18	-69	-120	-205	-273	-328	-378

CONCLUSIONS

Lake Shore Cryotronics has introduced a new diode thermometer, the DT-600 series, fabricated using state-of-the-art semiconductor techniques. This new diode thermometer maintains the benefits of previous cryogenic diodes (high signal, high sensitivity, wide temperature range, good stability, robustness, small physical size, small thermal mass / fast thermal response) and introduces three important new features. First, the device is available in die chip form as an off-the-shelf thermometer matched to a standard curve. Second, the DT-600 series is available in a tolerance band comparable to a platinum RTD tolerance band with tightest matching at room temperature, but with a standard curve that extends to 2 K. Third, unlike many other cryogenic diode thermometers, the DT-600 series has shown no evidence of switching.

REFERENCES

1. McNamara, A. G., "Semiconductor Diodes and Transistors as Electrical Thermometers," Rev. Sci. Instrum. **33**, 330 (1962).
2. Unsworth, J. and Rose-Innes, A. C., "Silicon pn-Junctions as Low Temperature Thermometers," Cryogenics **6**, 239 (1966)
3. Ray, J. and Chandra, G., "Low Temperature Themometric Characteristics of Silicon and Germanium Diodes," Cryogenics **14**, 414 (1974).
4. Swartz, J. M. and Swartz, D. L., "Cryogenic Temperature Sensors," Instrum. Tech. **33**, (1974).
5. Swartz, D. L. and Swartz, J. M., "Diode and Resistance Cryogenic Thermometry: A Comparison," Cryogenics **14**, 67 (1974).
6. Aldridge, R. V., "On the Behavior of Forward Biased Silicon Diodes at Low Temperatures," Solid State Electron., **17**, 607 (1974).
7. Treharne, R. W. and Riley, J. A., "A Linear Response Diode Temperature Sensor," Instrum. Tech. **59**, (1978).
8. Chopra, V. and Dharmadurai, G., "Effects of Current on the Low Temperature Characteristics of Silicon Diodes," Cryogenics **20**, 659 (1980).
9. Sondericker, J., "Production and Use of High Grade Silicon Diode Temperature Sensors," in *Advances in Cryogenic Engineering*, **27**, edited by R. W. Fast, Plenum Press, New York, 1981, pp. 1163-1171.
10. Rao, M. G., "Semiconductor Junctions as Cryogenic Temperature Sensors," in *Temperature, Its Measurement and Control in Science and Industry*, edited by J. Schooley American Institute of Physics, New York, 1982, pp. 1205-1211.
11. Rao, M. G., Scurlock, R. G. and Wu, Y. Y., "Miniature Silicon Diode Thermometers for Cryogenics," Cryogenics **23**, 635 (1983).
12. Rao, M. G. and Scurlock, R. G., "Recent Advances in Si and Ge Diode Thermometers," in *Proceedings fo the Tenth International Cryogenic Engineering Conference*, edited by H. Collen et al., Butterworth, Guildford, 1986, p. 418-421.
13. Krause, J. K. and Swinehart, P. R., "Reliable Wide Range Diode Thermometry," in *Advances in Cryogenic Engineering*, **31**, edited by R. W. Fast, Plenum Press, New York, 1985, pp. 1247-1254.
14. Igra, R. M., Rao, M. G. and Scurlock, R. G., "Thermometric Characteristics of the Improved Miniature Si Diodes," in *Proceedings fo the Eleventh International Cryogenic Engineering Conference*, edited by G. Klipping et al., Butterworth, Guildford, 1986, p. 617.
15. Szmyrka-Grzebyk, A. and Lipinski, "Low Temperature Current-Voltage Characteristics of Silicon Diodes Used as Thermometers," Cryogenics **33**, 222 (1993).
16. Dodrill, B. C., Krause, J. K., Swinehart, P. R. and Wang, V., "Performance Characteristics of Silicon Diode Cryogenic Temperature Sensors," in *Applications of Cryogenic Technology*, **10**, edited by J. P. Kelley, Plenum Press, New York, 1991, pp. 85-107.
17. Lake Shore Cryotronics, Inc., Westerville, OH, 43081, USA.
18. Scientific Instruments, Inc., West Palm Beach, FL, 33407, USA.
19. Oxford Instruments, Oxon, OX8 1TL, UK.
20. Tri-Research, St. Paul, MN, 55114, USA.
21. Courts, S. S. and Swinehart, "Long-Term Stability of a Cryogenic Diode," To be published in *Advances in Cryogenic Engineering*, **47**, American Institute of Physics, Melville, NY (2002).
22. Linenberger, D., Spellicy, E. and Radebaugh, R., "Thermal Response Times of Some Cryogenic Thermometers," in *Temperature, Its Measurement and Control in Science and Industry*, edited by J. Schooley, American Institute of Physics, New York, 1982, pp. 1367-1372.