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LONG-TERM STABILITY OF A CRYOGENIC DIODE THERMOMETER

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ABSTRACT

One of the most important qualities for a cryogenic thermometer is its ability to maintain its calibration upon thermal cycling. While it is most preferable to perform slow thermal cycling on cryogenic temperature sensors, it is not always practical to do so. Fast thermal cycling, or thermal shocking, induces stresses within the sensor that at best can cause shifts in calibration and at worst can cause catastrophic failure. From 1992 to present, ten Lake Shore Cryotronics model DT-470-SD cryogenic diodes have been used to aid the quality control testing of production devices. These diodes were randomly tested with production thermometers and subjected to thermal shock cycling between room temperature and 4.2 K during the production test cycle. This paper analyzes the data collected over the nine year period and reports the long-term stability of the ten diode thermometers at 305 K, 77.35 K, and 4.2 K after extensive thermal shocking. The data show that these devices exhibit long-term stability at each tested temperature to better than ±0.2 mK/thermal shock cycle. Individual diode thermometers exhibited a low temperature drift that could be in either the positive or negative direction, but the group as a whole averaged to a much lower drift overall drift.

INTRODUCTION

The forward voltage of a silicon diode excited at a constant current is a strong function of temperature. For some diode designs, this strong temperature dependence extends over the temperature range 1 K to 500 K, making them useful as a cryogenic thermometer. This temperature dependence has been investigated for nearly 40 years [1-15]. When compared to cryogenic resistive thermometer devices (RTDs) [5], diode thermometers yield a relatively higher signal and higher sensitivity over their useful temperature range. A typical diode response curve is shown in Figure 1 while the resulting temperature sensitivity is shown in Figure 2. In addition to ease of use, diode thermometers possess a number of other desirable characteristics. First, the diodes are manufactured

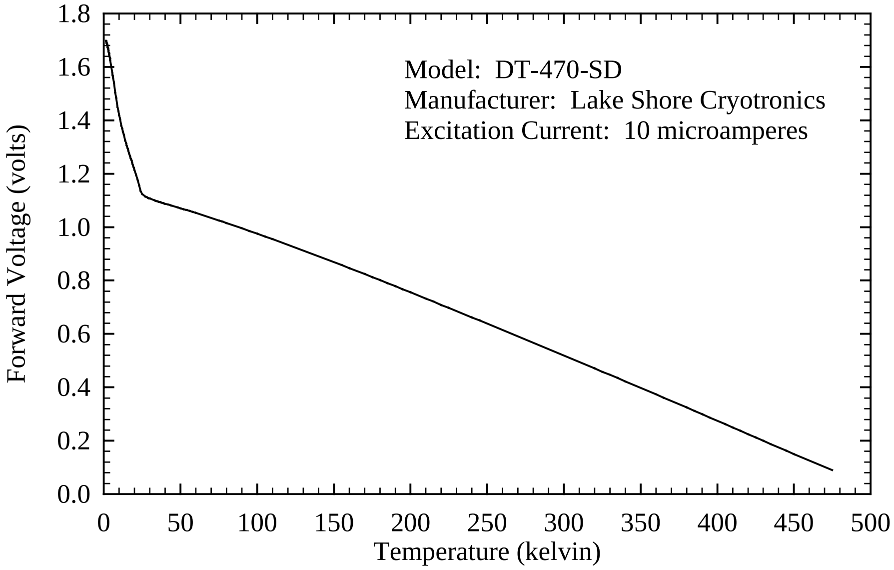

FIGURE 1. Typical forward voltage as a function of temperature for a typical cryogenic diode thermometer excited at 10 µA DC. (Data shown is for a Lake Shore model DT-470-SD cryogenic diode thermometer.)

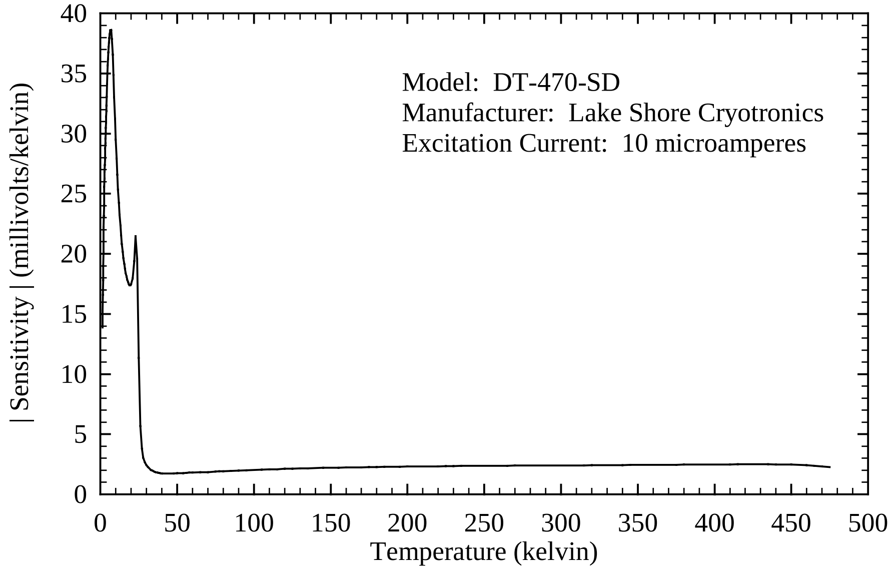

FIGURE 2. Typical temperature sensitivity as a function of temperature for a typical cryogenic diode thermometer rxcitated at10 µA. (Data shown is for a Lake Shore model DT-470-SD cryogenic diode thermometer.)

using standard semiconductor industry fabrication methods that yield highly uniform devices. When used as thermometers, this uniformity results in devices that are interchangeable within a given model type. With the notable exception of platinum RTDs and ruthenium oxide RTDs, most resistive cryogenic sensors require a costly individual calibration to achieve the accuracy available with a diode thermometer and its standard response curve. Second, the required instrumentation for diode thermometers is usually cheaper than that required for most resistive cryogenic thermometers. Third, unlike many types of cryogenic RTDs which require strain-free mounting making them very fragile, diode thermometers are very robust and can withstand mechanical shocks that would easily shift the calibration of the strain-free mounted RTDs. These features have enabled diodes to become the workhorse of the cryogenic thermometry industry. Diode thermometers are widely used in cryogenic coolers, cryopumps, infrared focal plane arrays, and a host of smaller applications.

The statement that diode thermometers are “robust” is the topic of this paper. Although there is not an exact definition of “robustness” when describing temperature sensors, the term carries the connotation of being somewhat resistant to damage due to mechanical shock and thermal stresses. Damage due to mechanical shock and thermal stresses cause a sensor’s response curve to shift. One of the most important criteria for a thermometer is its ability to repeat a measurement upon thermal cycling. This characteristic is called stability. As with the term “robustness”, there is no universally recognized standard for defining the stability of a temperature sensor. However, it is intuitive to speak of short-term stability as being the repeatability over a few thermal cycles and long-term stability as being the repeatability over many thermal cycles. In practice, it is necessary to consider how the thermal cycles are performed – rapid thermal shocking is much more detrimental to a temperature sensor than slow thermal cycling. This paper examines the long-term stability of ten Lake Shore model DT-470-SD diode temperature sensors measured at 4.2 K, 77.35 K, and 305 K over large numbers of thermal shock cycles.

EXPERIMENT

As a standard step in their production process, all Lake Shore cryogenic thermometers undergo thermal cycling from room temperature to 4.2 K in a quality control test area. As is common practice, most cryogenic thermometers are thermally cycled multiple times for thermal stress conditioning with test data collected during the thermal cycling to verify stability specifications. Over the past nine years, ten Lake Shore model DT-470-SD diode thermometers have been included as test standards on random diode production runs during this quality control testing. The data obtained from these standards were used to verify test and measurement equipment during production runs and to develop statistical process control charts for the testing process. These test standards were obtained from production stock with no special testing or selection. Table 1 lists the serial number of these sensors, the total number of room temperature-to-4.2 K thermal shocks the sensor has undergone, and the period over which the thermal shocks occurred. This diode thermometer model was introduced by Lake Shore Cryotronics, Inc. [16] in 1986 and was well characterized by Krause and Dodrill [17] and in product literature [18].

It should be explicitly stated that the data collected and presented in this paper were not the result of a planned experiment, but rather an after-the-fact analysis of data collected during production quality control testing.

TABLE 1. Model number, serial number, period of use, and number of LHe cycles for the diodes analyzed in this paper.

Serial Number	Number of thermal shocks	Period of use
D01563	351	Aug. 1992 – Feb.1995
D01564	768	Aug. 1992 – Nov. 1997
D04792	261	Mar. 1993 – Apr. 1995
D06466	318	Mar. 1995 – Mar 1997
D16733	327	Oct. 1995 – Oct 1997
D21765	144	Apr. 1997 – Jun. 1998
D28655	279	Jun. 1998 - Present
D28657	678	Jun. 1998 - Present
D28712	624	Jun. 1998 - Present
D28719	249	Jun. 1998 - Present

The diode chips are packaged into a hermetically sealed package consisting of a flat sapphire base with an alumina body and lid. Diode chips are eutectically bonded to the metallized sapphire, and wire bonds are made to feedthrough traces on the interior of the package. Kovar leads are brazed to the feedthrough traces on the exterior of the package. The overall size of the package is 1 mm x 1.9 mm x 3.2 mm. Detailed construction information is available in reference [18].

During quality control testing, a standard diode thermometer was randomly loaded onto a test probe with the production devices under test. The sensors were thermally shocked by rapid immersion into a cryogen. A typical production run consisted of:

1) A data point at 305 K in a specially designed, temperature controlled oven.
2) A data point at 77.35 K after rapid immersion into liquid nitrogen.
3) A data point at 4.2 K after rapid immersion into liquid helium.
4) A thirty-minute warm-up to room temperature.
5) A second data point at 4.2 K after rapid immersion into liquid helium.
6) A thirty minute warm-up to room temperature.
7) A third data point at 4.2 K after rapid immersion into liquid helium.

The final data collected on each run for each device included one 305 K data point, one 77.35 K data point, and three 4.2 K data points. Each data point taken for the test standards was measured at the recommended diode excitation current of 10 μA DC.

Data collection was computer automated. The instrumentation consisted of a Keithley 224 current source, a Hewlett Packard 3457A digital voltmeter, and a Keithley 706 Scanner mainframe with model 7065 scanner ten-channel, four-wire, low thermal EMF scanner cards to connect the instrumentation to each sensor. Measurements were performed in four-lead fashion to eliminate lead resistance. Current reversal, a common technique for eliminating thermal EMFs in resistors, could not be performed due to the semiconductor nature of the device. However, the thermal EMFs generated equate to small temperature errors when converted. A 1.0 μV thermal EMF equates to a 0.52 mK offset at 77.35 K and a 0.03 mK offset at 4.2 K.

The temperature of the room-temperature oven varied by ±0.05 K while the temperature of the liquid nitrogen bath varied by as much as +0.2 / -0.5 K due to changes in atmospheric temperature. Platinum RTD standards were used to correct for deviations in the actual temperature of both the room-temperature bath and the liquid nitrogen bath. The temperature of the liquid helium bath only varied by about ±10 mK due to changes in atmospheric pressure. This was sufficient repeatability of the liquid helium bath temperature for the quality control test so no attempt was made to correct for temperature deviations at that temperature.

Three identical test stations are maintained and measurements have been performed on all three stations. The error analysis must include the possible errors from 1) the calibration of the platinum RTD used to correct the 77.35 K and 305 K diode measurement, 2) the voltmeter accuracy in measuring the platinum RTD, 3) the current source accuracy in measuring the platinum RTD, 4) the voltmeter accuracy in measuring the standard diode, and 5) the current source accuracy in measuring the standard diode. Below room temperature, in-liquid measurements eliminate the temperature offsets due to variations in mounting of these high power dissipation devices. All totaled, the repeatability of the measurement from an equipment standpoint is ±1.65 mK at 4.2 K, ±25.2 mK at 77.35 K, and ±48.6 mK at 305 K. Deviations and trends above this level are attributed to the long term stability of the diode test standards.

Devices taken out of service were done so for one of two reasons. First, the constant soldering to the kovar leads eventually dissolved the leads to the point that they were too short for practical use. These devices were retired. Second, some devices were removed from service in the quality control area for use in another laboratory area.

DATA

The data reported are reduced from voltage measurements to the voltage difference from the initial reading, and then finally to the equivalent temperature difference, ΔT using

$$\Delta T = \frac{V_{Measured} - V_{Initial}}{\left(\frac{dV}{dT}\right)} \qquad (1)$$

These data are plotted against the number of thermal shocks from room temperature to 4.2 K. As an example, Figure 3 shows the reduced data versus the number of thermal shocks at 4.2 K, 77.35 K, and 305 K for device serial number D01564. For each set of data, regression analysis was applied to fit the data. Linear regression was found to provide the best fit. For each temperature in Figure 3, the calculated line of best fit is shown. The slope of the line of best fit represents the calibration shift per thermal shock cycle.

The line of best fit was determined for each standard diode sensor at each of the three temperatures. These data are shown in Figure 4 for temperatures of 4.2 K, 77.35 K, and 305 K respectively. As stated above, the slope is the figure of merit as it represents the value that can be expected for long-term stability. The slope data are tabulated for each device and each temperature in Table 2. At 4.2 K, the stability ranges from –0.0297 to +0.1775 mK/thermal shock cycle. At 77.35 K, the stability ranges from –0.0590 to +0.1104 mK/thermal shock cycle. Finally, at 305 K, the stability ranges from –0.1358 to +0.1685 mK/thermal shock cycle. It should be noted from Figure 4 that the individual devices can drift either positive or negative in temperature shift, but the group as a whole averages to a long term drift that is smaller than the individual drift rates. This is especially true at 77.35 K and even more so at 305 K.

TABLE 2. Average equivalent temperature shift at 4.2 K, 77.35 K, and 305 K per thermal shock cycle for each diode thermometer in the study.

Serial Number	Average temperature shift per thermal shock cycle at temperature (millikelvin/cycle)		
	4.2 K	77.35 K	305 K
D01563	+0.0501	-0.0182	-0.0485
D01564	+0.0220	+0.0336	+0.0214
D04792	+0.0251	-0.0202	+0.1470
D06466	+0.0809	-0.0412	+0.1685
D16733	+0.0508	-0.0446	+0.0254
D21765	+0.1775	-0.0589	-0.0955
D28655	-0.0113	+0.0621	+0.0823
D28657	+0.0027	+0.0379	-0.0674
D28712	+0.0062	+0.0421	-0.0164
D28719	-0.0297	+0.1104	-0.1358
Overall Weighted Average:	+0.0260	+0.0187	+0.0048

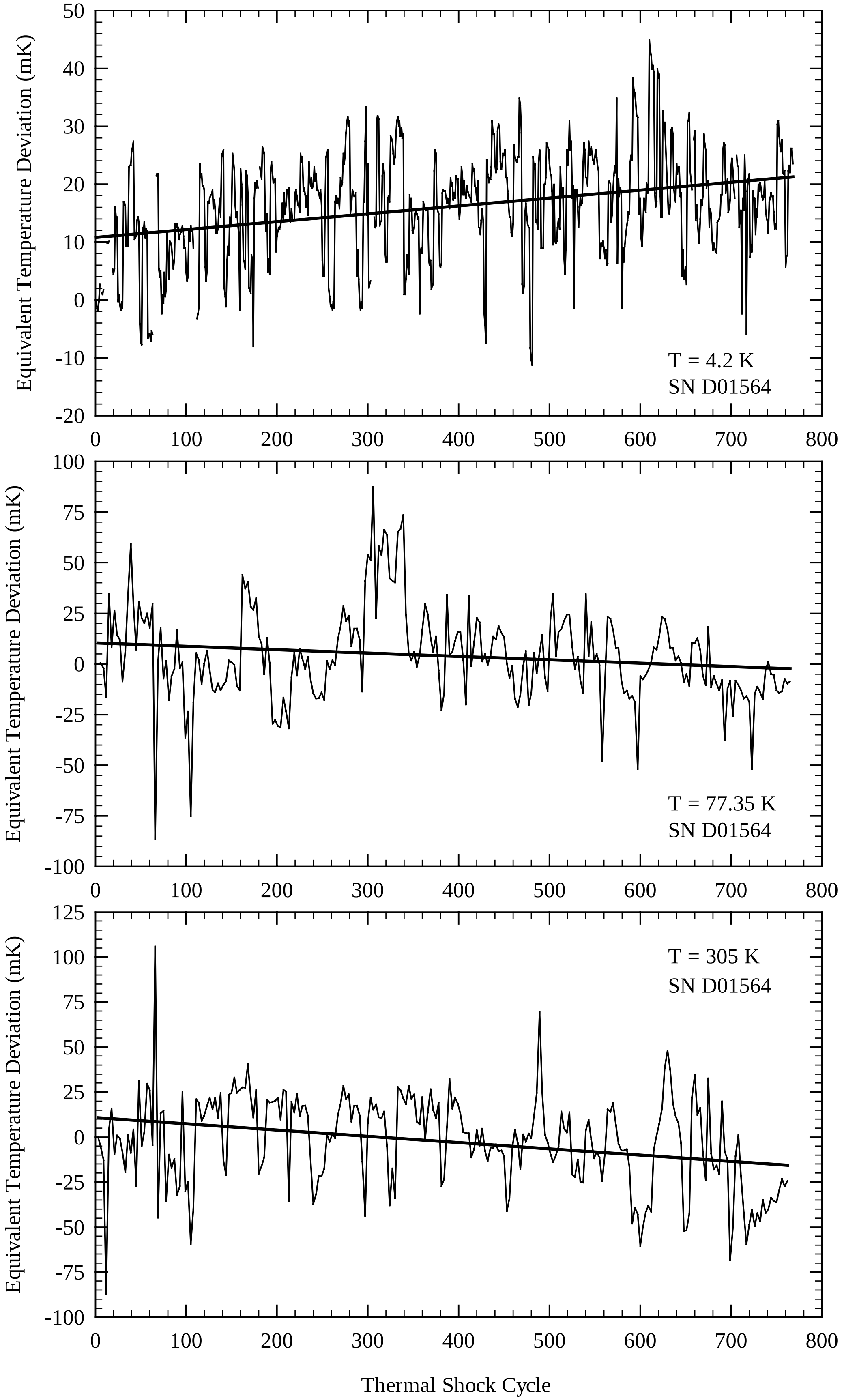

FIGURE 3. Equivalent temperature difference, ΔT, versus thermal shock cycle at 4.2, 77.35K and 305 K for device serial number D01564.

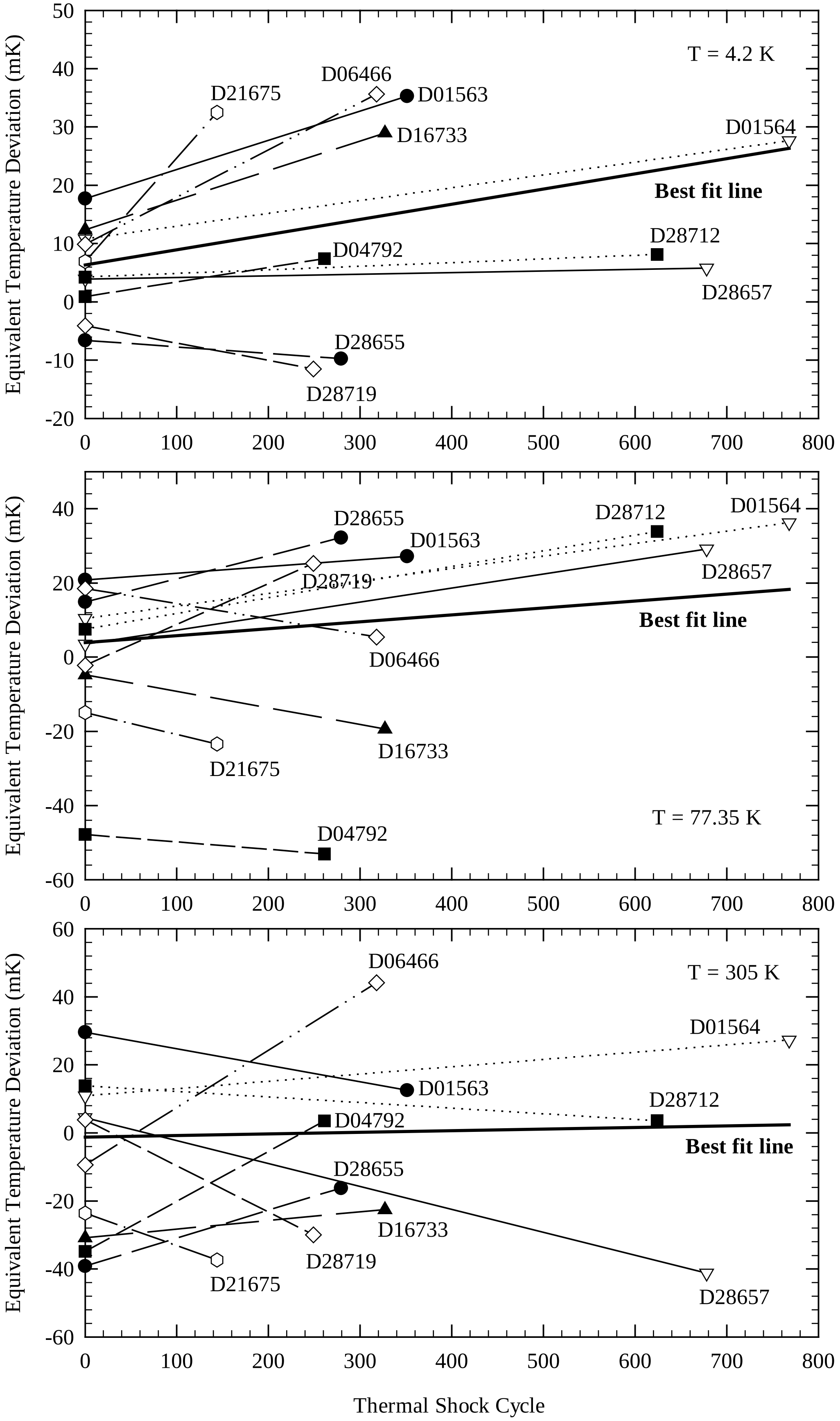

Figure 4. Lines of best fit for the equivalent temperature offsets versus number of thermal shock cycles at 4.2 K, 77.35 K, and 305 K for each diode in the study.

CONCLUSIONS

Stability measurements were performed on ten Lake Shore Cryotronics model DT-470-SD cryogenic diode thermometers at 4.2 K, 77.35 K, and 305 K. These ten devices were thermally cycled from room temperature to 4.2 K a combined 4000 times without failure, demonstrating an impressive robustness. Data were taken during the thermal cycling and analyzed to provide an estimate of the long term stability of the cryogenic diode thermometer. The data indicate that long term stability at 4.2 K, 77.35 K, and 305 K should be better than ±0.2 mK per thermal shock cycle. It should be pointed out that slow thermal cycling (as opposed to the fast thermal shocks performed in this work) would be expected to significantly improve upon this long-term stability value. The data also show that individual diodes could have long-term drifts that could be either positive or negative, but the group as a whole averaged out to a much lower drift rate, especially so at higher temperatures.

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, pp. 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. Lake Shore Cryotronics, Inc., Westerville, OH, 43081, USA.
17. 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.
18. Lake Shore Cryotronics, Inc., *Temperature Measurement and Control Product Catalog* (1999).