Test Structure and Software for Measuring Thin Film TCR

- **Evaluate & Monitor Low TCR Films**
- **Range: Ambient to 600°C**
- **Sensitivity: 1ppm/C° in 100C° Span**
- **> 100X Faster Than a Hot Chuck**
- **Customized Heated Test Structure**
- **EMPAC & Acquire Test Software**
- **Temperature & Time Plots**
- **TCR for 5 Temperature Spans**
- **Thermal Cycling Hysteresis**
- **Structure Integrity Checks**

Product Deliverables

This product offering consists of test software, a GDSII compatible test structure, testing of at least one wafer, and one day of training at Reedholm. It can be ordered with a new Reedholm test system or retro-fitted in a Reedholm system which has at least three VFIF's and a DMM-16.

TCR Test Structure

The test structure can be implemented with any process which permits a vertical stack consisting of a heating layer, an insulator on which the precision thin film is placed, and another insulator on which a metal thermometer line is placed. Figure 1 is an illustration of the structure using a polysilicon heater.

Use of Low TCR Films

Performance of many precision integrated circuits is dependent on low temperature coefficient of resistance (TCR) resistors. For example, analog to digital and digital to analog converters typically use low TCR films in ladder networks and as feedback resistors. Some signal processing IC's make use of low TCR films for gain setting. TCR values, matching, and stability are extremely important in such applications.

Reasons to Monitor TCR

- Thin film TCR parameters are highly dependent on processing, and no process is 100% in control 100% of the time.
- TCR varies with temperature, and might not be in compliance over the entire range of the product.
- Thin films are physically altered by temperature cycling, and the resultant resistance shifts may be too large to tolerate.

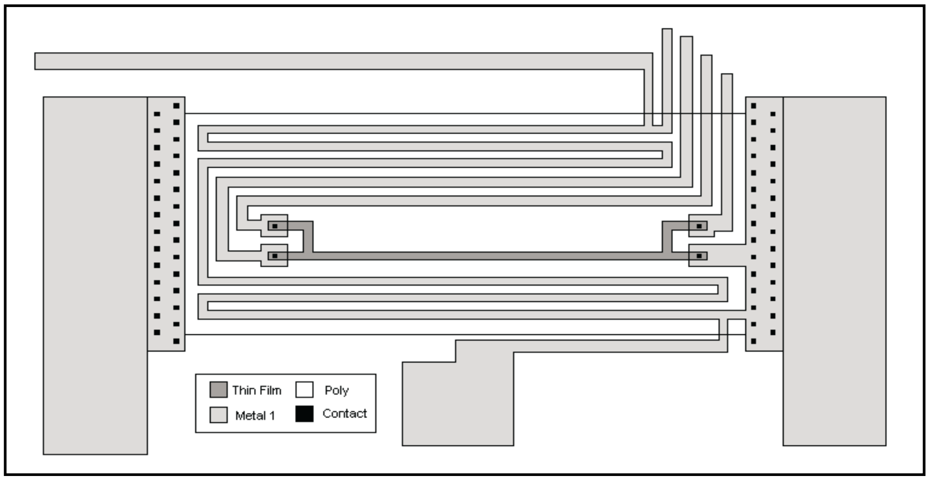


Figure 1 - TCR Test Structure

Performance Advantages

Semiconductor companies which deposit and pattern low TCR thin films can benefit from use of this toolset:

- It produces unambiguous TCR results for development and process control applications.
- Test times are two orders of magnitude faster than with a hot chuck.
- It makes measurements that are highly impractical with a hot chuck. For instance, TCR is measured for more than one temperature span. Also, resistance hysteresis due to temperature cycling is just one of several TCR quality output parameters.
- Only the structure is heated, so the harmful effects of heating the entire wafer are eliminated.

TCR of Metal Lines and Thin Films

TCR is defined as the rate of change of resistance with temperature. For metal lines used as IC interconnects, TCR's are relatively large and normally expressed as a percentage change per unit of temperature (%/C°).

Thin film TCR's used for precision circuit elements are much lower, and are expressed in parts per million change per unit of temperature (ppm/C°).

Metal Line Interconnect TCR's

Metal interconnects are processed using alloys with small amounts of impurities which improve quality and reliability. Since interconnect lines are almost pure metal, their TCR's are close to those of the dominant metal in the alloy. In particular, aluminum line TCR's range from 0.31 to 0.38%/C°, and are quite stable unless temperatures are raised to a level high enough to anneal their grain structure. As with pure metals, linearity of resistance versus temperature is quite good. Their extremely linear behavior with temperature is why metals like platinum are used for precision temperature sensing in many industrial applications.

Precision Thin Film TCR's

Low TCR films are made from alloys which have nearly zero TCR over the operating ranges of precision integrated circuits. However, low TCR films exhibit severe non-linearity of resistance versus temperature at very high and very low temperatures.

While TCR's are often very low, exactly zero TCR is seldom achieved. Due to random variations, deviation from zero TCR can be described statistically with a Gaussian distribution. Furthermore, TCR is not constant over the range of interest, and its variability might make it unsuitable even though end point measurements indicate satisfactory behavior.

Figure 2 illustrates the significant difference in the resistance versus temperature relationships of a metal interconnect and a low TCR thin film resistor.

Figure 3 shows the change in resistance over a more narrow range for both types of resistors. Note that suitable scaling for a +20ppm/C° TCR plot produces a nearly vertical slope for the metal line resistance. That is because a TCR of 0.38%/C°, or 3800ppm/C°, is 190 times the TCR of a 20ppm/C° resistor.

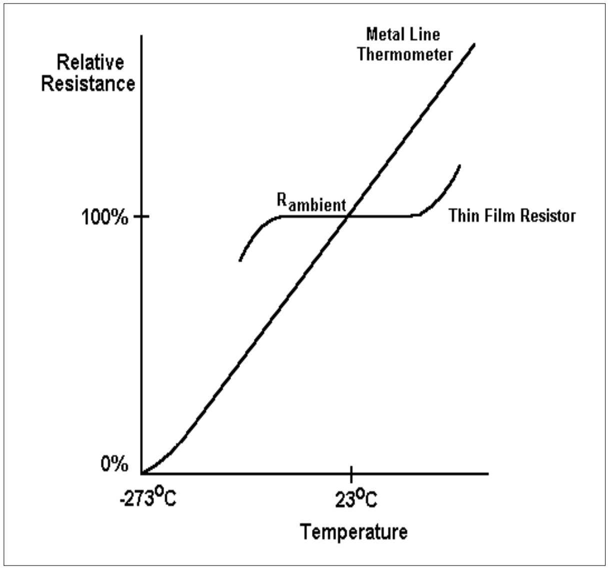


Figure 2 - Resistance vs. Temperature

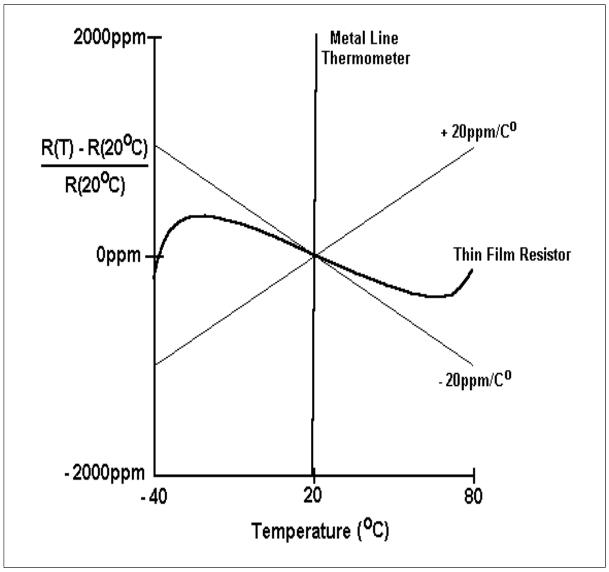


Figure 3 - Change in Resistance vs. Temperature

TCR Test Structure Elements

The test structure elements shown in Figure 1 can be represented by the electrical schematic in Figure 4. Power supplies and the digital meter are software controlled by the test algorithm. Rectangles surrounding the “Px” identifiers represent probe pads.

Thermometer

The thermometer is a metal interconnect line patterned as a four terminal resistor. TCR testing software uses a metal line to sense temperature change resulting from applying current to an underlying heater element. While the high TCR of a metal line makes it a poor choice as a circuit element, its stability and extremely linear change of resistance with temperature make it an excellent temperature sensor.

As long as a metal line is stable throughout the temperature range of use, it is suitable as a sensitive temperature sensor. TCR of the thermometer needs to be accurately measured in order to accurately determine temperature. It is straightforward to measure TCR using the NIST technique.

When placed on an insulator above the thin film resistor, or device under test (DUT), relative physical dimensions of the test structure ensure that the thermometer line is close to the DUT temperature. When the process being used does not permit such vertical stacking, the DUT can be placed on the same plane as the metal line sensor and intertwined with it to maximize thermal coupling. Since temperature changes are used for TCR determination, extremely tight thermal coupling from the DUT to the thermometer is not required. That is because heat loss from each is small compared to the heat coupled from the heater.

Device Under Test (DUT)

The DUT is a simply a low TCR film patterned as a four terminal resistor and placed on an insulator overlaying the heater.

Heating Element

To date, structure heaters have been made from either polysilicon or buried epi. Polysilicon heaters have much higher thermal resistance and lower effective thermal mass than buried epi heaters. Thus, it takes considerably more power to heat the epi layer to a given temperature. Also, an epi heater has a much higher time constant for temperature response to a given heater current.

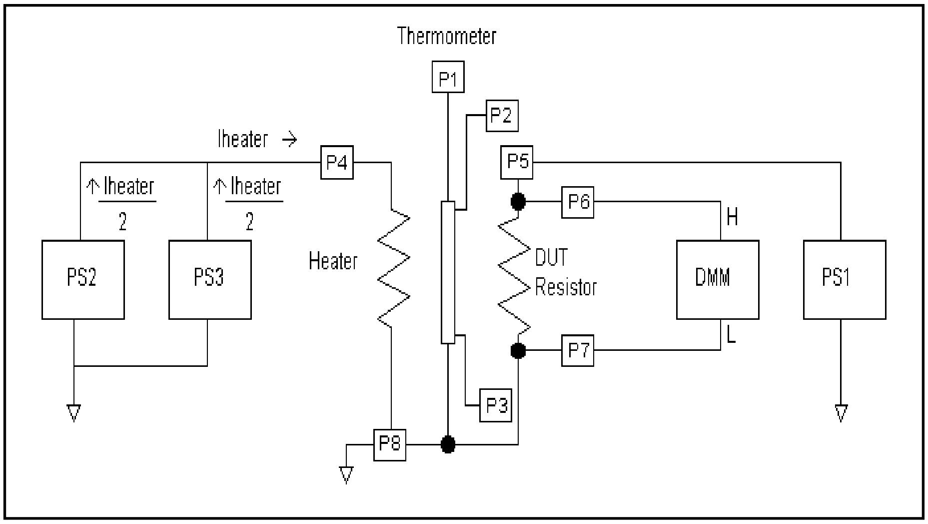
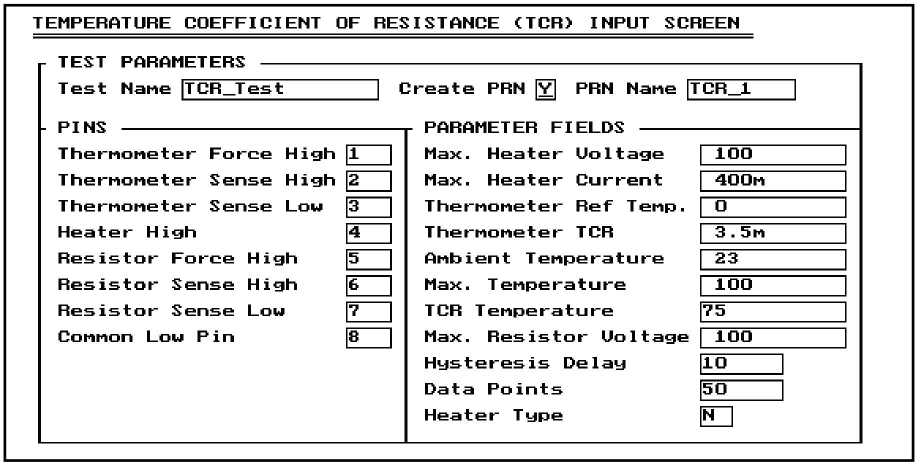


Figure 4 - TCR Structure Test Schematic

Creating and Modifying TCR Test Software

The thin film TCR test set-up screen shown in Figure 5 is selected from the Reedholm EMPAC test editor menu. Cell inputs are checked for compliance, errors reported, and correction required before testing starts. The key input parameters are:

- Probe pad assignments.
- Maximum stress conditions.
- Thermometer TCR and temperature at which TCR has been measured.
- Ambient temperature of the chuck so starting temperatures can be different than ambient.
- Temperature at which TCR above ambient is to be measured.
- Delay for cool down and physical recovery before resistance shift due to thermal stress is measured.
- Number of data points for viewing results using Reedholm's EMAGE software.



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TEMPERATURE COEFFICIENT OF RESISTANCE (TCR) INPUT SCREEN

TEST PARAMETERS
Test Name [TCR_Test]            Create PRN [Y]  PRN Name [TCR_1]

PINS                              PARAMETER FIELDS
Thermometer Force High [1]        Max. Heater Voltage      [100]
Thermometer Sense High [2]        Max. Heater Current      [400m]
Thermometer Sense Low  [3]        Thermometer Ref Temp.    [0]
Heater High            [4]        Thermometer TCR          [3.5m]
Resistor Force High    [5]        Ambient Temperature      [23]
Resistor Sense High    [6]        Max. Temperature         [100]
Resistor Sense Low     [7]        TCR Temperature          [75]
Common Low Pin         [8]        Max. Resistor Voltage    [100]
                                  Hysteresis Delay         [10]
                                  Data Points              [50]
                                  Heater Type              [N]
```

Figure 5 - TCR Test Input Screen

TCR Equations

To make best use of Reedholm's TCR software, TCR of the thermometer element and the temperature at which TCR has been measured must be known. Temperature is required because of the way in which TCR is specified. That is, the equation for TCR, in ppm/C°, is a function of the temperature span, the resistance change in that span, and the resistance at the specifying temperature.

$$TCR = \frac{\Delta R}{R\Delta T} x10^{6} \tag{1}$$

Equation (1) can be manipulated so that the TCR of thermometer line at ambient temperature (TCR_{TA} & T_A respectively) can be determined using the reference temperature and TCR (T_R & TCR_{TR} respectively) of the thermometer line.

$$TCR_{TA} = \frac{1}{\frac{1}{TCR_{TR}} + (T_R - T_A)} \tag{2}$$

By knowing TCR_{TA}, the change in structure temperature from ambient to the test temperature, T_T, can be determined from measurements of ambient and test thermometer resistances (R_{TA} & R_{TT} respectively).

$$T_T - T_A = \frac{R_{TT} - R_{TA}}{R_{TA} TCR_{TA}} \tag{3}$$

The ambient TCR of the thin film resistor, TCR_{RA}, can be calculated using its resistance at ambient and test temperatures (R_{RA} & R_{RT} respectively).

$$TCR_{RA} = \frac{R_{TR} - R_{RA}}{R_{RA}(T_T - T_A)} \tag{4}$$

By combining Equations (3) and (4), an explicit calculation for thin film ambient TCR can be made based solely on resistance measurements and the metal line thermometer TCR.

$$TCR_{RA} = \frac{R_{TA}(R_{RT} - R_{RA})}{R_{RA}(R_{TT} - R_{TA})} TCR_{TA} \tag{5}$$

TCR Measurement Uncertainties

Uncertainties in measuring thin film TCR is a function of test setup, instrumentation specifications, and physical characteristics of the structure.

To estimate effects on measurement sensitivity, the equation for TCR_{RA} can be written as:

$$TCR_{RA} = \left(\frac{\frac{R_{RT}}{R_{RA}} - 1}{\frac{R_{TT}}{R_{TA}} - 1} \right) TCR_{TA} \qquad (6)$$

All resistance values in Equation (6) are made using one of two currents; one for thin film measurements and another for thermometer measurements. Inserting appropriate V/I relationships and keeping the same subscripts, the equation can be written as:

$$TCR_{RA} = \left(\frac{\frac{V_{RT}}{V_{RA}} - 1}{\frac{V_{TT}}{V_{TA}} - 1} \right) TCR_{TA} \qquad (7)$$

Inspection of Equation (7) and use of the same currents for two different temperatures lead to these observations on TCR measurement uncertainties.

- Thin film TCR uncertainty is not dependent on test current accuracy. It is only dependent on four voltage measurements and the metal line TCR.
- If it is necessary to control thin film TCR within 1%, then metal line TCR must be known with much lower than 1% error.
- V_{RT} and V_{RA} are close to the same value when TCR is small, so the numerator term (V_{RT}/V_{RA} - 1) is the difference between large numbers that effectively multiplies uncertainties in both V_{RA} and V_{RT}.
- Uncertainty in the other two voltage terms are multiplied by a smaller number. For a metal line TCR of 0.333%/C° and a temperature span of 100C°, the denominator term of (V_{TT} /V_{TA} -1) would be equal to 0.333, thereby multiplying uncertainties in V_{TT} and V_{TA} by three.
- Errors common between V_{RT} and V_{RA} or between V_{TT} and V_{TA} are canceled. One result is the effective elimination of the effects of self heating. That is, self heating of either the film resistor or the thermometer lines increases the respective voltage measurements by the same amount, so ratios are unaffected. Another result is that systematic gain and offset errors in voltage measurements are canceled. The only important measurement specifications are those that are not systematic.

Voltage Resolution

Incremental non-linearity in the measurement analog to digital converter is an uncertainty that is not systematic. Another uncertainty is noise. Resolution of the DMM-16 required for thin film TCR is ~30ppm (1 of 32,768) with incremental non-linearity of + ½ least significant bit (lsb). Use of line synchronous averaging reduces noise contributions to <<1/2lsb. Thus, any voltage ratio could have a numerator error of +1/2lsb while the denominator is off by -1/2lsb. In combination, the ratio error would be +1lsb through application of the binomial expansion.

Example Calculation of TCR Uncertainty

Uncertainty in thin film TCR cannot be stated as simply as instrumentation measurement uncertainties. It needs to be calculated for actual test conditions. The example uncertainty calculation described in this data sheet is based on these assumptions:

- Thermometer measurement voltage is 75mV at ambient. That is 30% of full scale.
- Thin film TCR is 20ppm/C°.
- Thin film measurement is at 50% of scale.
- Temperature span is 100C°.
- Thermometer TCR is 0.333%/C.
- Thermometer TCR uncertainty is 0%.

While not derived in this document, differential analysis of Equation (7) yields these calculations for worst case uncertainty.

Thermometer measurements (V_{TT} & V_{TA}):

- 0.003% x 1/0.30 x 1/0.333 = 0.03%

Resistance measurements (V_{RT} & V_{RA}):

- 0.003% x 1/0.5 x 1/0.002 = 3%

Thermometer TCR uncertainty (TCR_{TA}):

- 0%

Total worst case uncertainty for TCR_{RA}:

- 3.03% of 20ppm = 0.606ppm

For this example, no uncertainty has been associated with the thermometer TCR, but that is an unlikely occurrence. For instance, a thermometer TCR error of 5% would increase worst case error for TCR_{RA} to 8%, or 1.6ppm.

It is really not appropriate to use worst case analysis for the various error terms. A statistical treatment is called for. Assuming that the terms have normal distributions and are orthogonal, the expected uncertainty limits would be <<1.5%, or 0.3ppm.

Acquiring TCR Test Data

TCR tests produce parametric data for process control as well as graphical data useful in development and troubleshooting.

Graphical Results

If a “Y” is placed in the “Create PRN” cell of the input screen shown in Figure 5, the following data files are created for viewing and manipulation within Reedholm’s EMAGE software product. Figure 6 is the output plot of thin film TCR versus temperature. Additional plots are generated of temperature versus:

- Resistance
- Heater Current
- Heater Voltage
- Heater Power
- Thermal Resistance
- Temperature Error

In addition to the temperature plots, plots are produced of dynamic response.

- Thermometer Thermal Time Constant
- Thin Film Resistor Thermal Time Constant

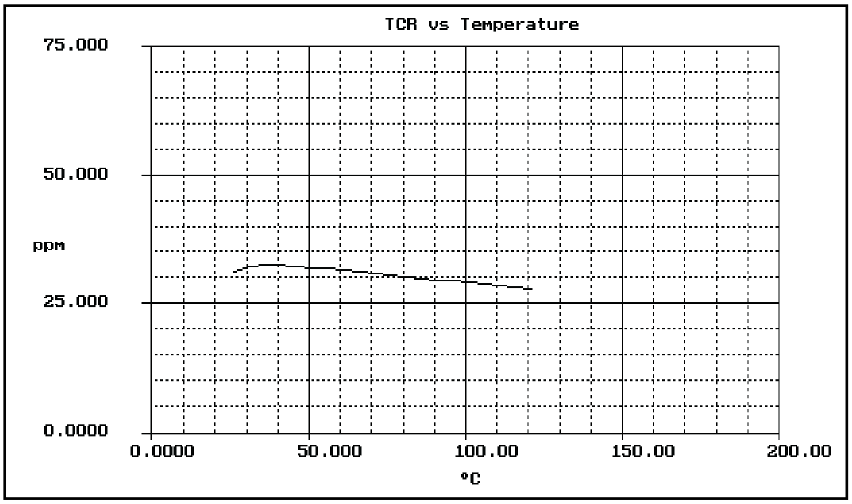
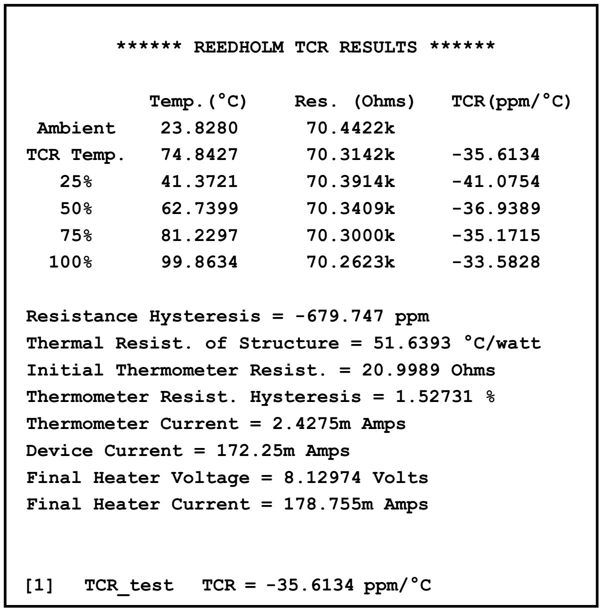


Figure 6 - Thin Film TCR vs. Temperature

Parametric Data

An array of result parameters is created. Any or all can be placed in the *.FMT file created by Reedholm’s Acquire software. All parameters may prove useful while the TCR tool set is being readied for production. When using EMPAC, a post test screen (Figure 7) displays the full array of parameters generated during TCR test executions including:

- Ambient Thin Film TCR’s for Five Temperatures
- Thermal Resistance
- Resistance Shift of the Thermometer and Thin Film Resistor due to Thermal Stress (Hysteresis)
- Ambient Thin Film Resistance
- Heater Current and Voltage
- Test Currents



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            ****** REEDHOLM TCR RESULTS ******

             Temp.(°C)    Res. (Ohms)    TCR(ppm/°C)
 Ambient      23.8280      70.4422k
TCR Temp.     74.8427      70.3142k      -35.6134
   25%        41.3721      70.3914k      -41.0754
   50%        62.7399      70.3409k      -36.9389
   75%        81.2297      70.3000k      -35.1715
  100%        99.8634      70.2623k      -33.5828

Resistance Hysteresis = -679.747 ppm
Thermal Resist. of Structure = 51.6393 °C/watt
Initial Thermometer Resist. = 20.9989 Ohms
Thermometer Resist. Hysteresis = 1.52731 %
Thermometer Current = 2.4275m Amps
Device Current = 172.25m Amps
Final Heater Voltage = 8.12974 Volts
Final Heater Current = 178.755m Amps


[1]   TCR_test   TCR = -35.6134 ppm/°C
```

Figure 7 - EMPAC Post TCR Test Screen

Enhancing TCR Accuracy with Software

Several error- reducing techniques are used in order to minimize uncertainty of TCR measurement.

- Line frequency noise is eliminated by integrating measurements over five line frequency periods.
- Thermal offset voltage in the thermometer measurement path is eliminated by measuring the voltage drop at zero current and subtracting it from the voltage measured with current flowing.
- Thermal offset voltages in the thin film resistor path are eliminated by measuring voltage drop for equal magnitude positive and negative currents and then averaging the two values.
- Digitization uncertainty in setting current for the power supplies is eliminated by querying the supplies for the value stored in the digital to analog converters and using that value in calculations involving current.

Error Detection to Assure Data Quality

Error trapping and reporting are important parts of Reedholm test algorithms. Even the lowest level test software is prevented from damaging the instrumentation. Actions which might otherwise cause a system software crash are trapped. Erroneous test results are flagged.

Some test problems are so severe that the test is not allowed to start or the test is halted. These are assigned unique numbers and multiplied by the constant 1E+22. Data results greater than 1E+22 are likely to be errors and the results may be invalid. For such cases, RIRESULTS array elements are set to 1E+20.

#	Encoded Error Description
1	Not used.
2	Not used.
3	Error in measuring temperature.
4	Cannot force 75mV on thermometer. Thermometer shorted.
5	Not used.
6	Not used.
7	Thermometer appears open, not current limited for max. thermometer voltage.
8	Resistor appears open, not current limited for max. resistor voltage.
9	Not used.
10	Heater appears open, not current limited for max. heater voltage.
11	Not used.
12	Not used.
13	Not used.
14	Not used.
15	Divide by zero attempted.

Figure 8 - Integer Values of Error Flags

Starting the TCR Test

Besides test plan creation and data output, TCR test software performs three distinct actions during test execution: structure checking, ramping temperature, and measuring hysteresis.

Checking Structure Integrity

The heater, thermometer, and thin film resistor are checked before testing starts. Except for the heater, current is ramped until a voltage or power threshold is reached. Those threshold producing currents are used for all succeeding tests. These checks are performed:

- The heater is checked by forcing 50mA and measuring its voltage drop. Testing does not start if heater resistance is <1Ω or if a supply used for heating goes out of current limit.
- The thermometer is checked by initially forcing 95µA and measuring its voltage drop. Then current is ramped up until voltage across the thermometer is 75mV. Thermometer resistance is calculated at that threshold current and used as the ambient reference resistance. Testing does not start if the power supply used for measurement goes out of current limit.
- The thin film resistor is checked by forcing 1µA and measuring its voltage drop. This current is ramped up until power dissipated in the resistor is approximately 1mW or until the voltage drop reaches 80% of the maximum compliance voltage. Having a 1mW power limit minimizes self heating effects. Resistance at that threshold power is the ambient resistance used for calculating thin film. Testing does not start if the power supply used for measurement goes out of current limit.

Starting the Temperature Ramp

The temperature ramp has at least six temperature settings: ambient, maximum, user specified, and three at 25%, 50%, and 75% of the difference between ambient and maximum. If a *.PRN file is requested, the user can specify up to 50 steps between ambient and maximum.

Before forcing enough heater current to appreciably raise the structure temperature, the following data is taken at ambient temperature:

- Actual structure temperature
- Thin film resistor value
- Heater voltage
- Heater current

Initial Thermal Resistance

The first step in determining thermal resistance is to force a current producing 0.1W in the heater and making continuous temperature measurements until temperature is stabilized. Then, current is ramped up until temperature is at least 5°C above ambient. Thermal resistance is calculated from the actual temperature rise and power delivered to the heater. Testing does not start if temperature cannot be raised >5°C above ambient.

Ramping Temperature

After initial checking, thermal resistance is used to predict the heater power required to produce the desired ramp temperatures. This sequence is performed at each step of the ramp until temperature is within 0.2°C of the desired level or within 0.25% of the temperature rise, whichever is greater:

- Heater current is set to the square root of the required power divided by the heater resistance. Figure 9 shows a typical current ramp plot generated from a data file. Likewise, Figure 10 displays heater power.
- Temperature is measured, thermal resistance updated, and a new value for power is calculated from the difference between desired and actual temperatures. Excellent temperature control of the TCR routine is shown in Figure 11.
- Data is stored at each temperature.

The ramp is terminated if any heater current supply goes out of current limit or the measured temperature fails to converge on the desired temperature. Upon test termination, measurements from the previous step are stored as the last data points.

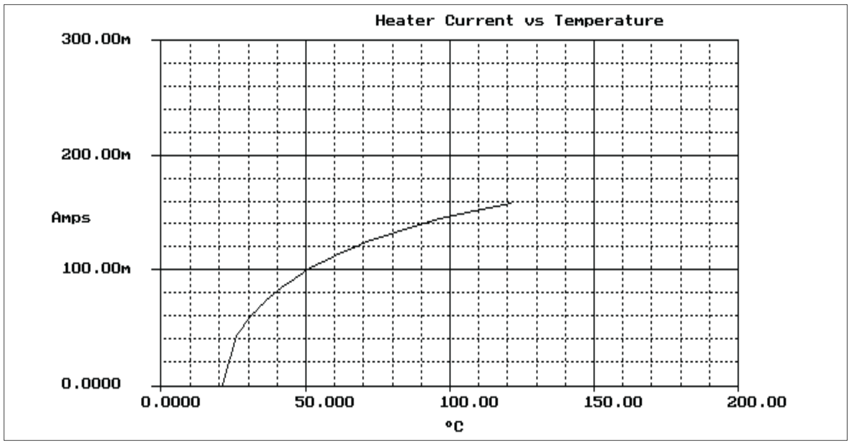

Figure 9 - Current Required for Temperature Ramp

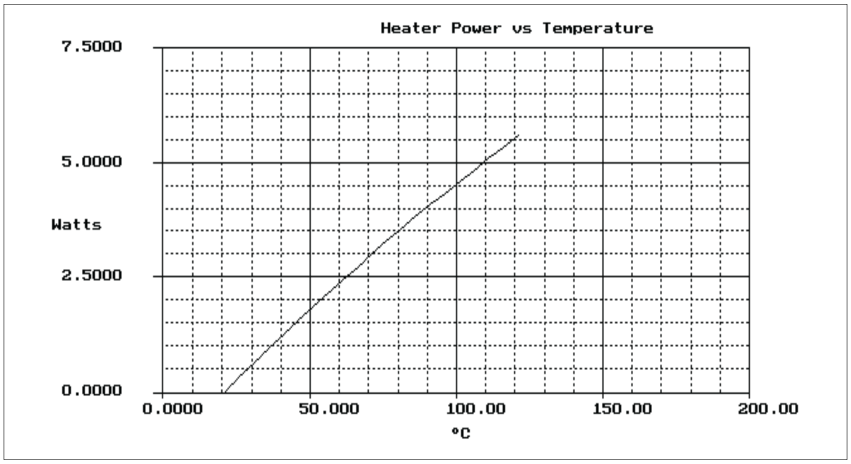

Figure 10 - Power Required for Temperature Ramp

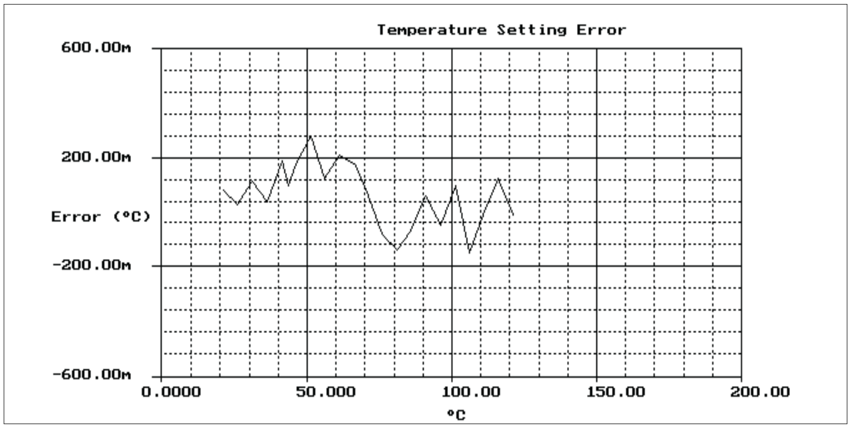

Figure 11 - Calculated Error in Setting Ramp Temperature

Checking for Resistance Hysteresis

Hysteresis measurements of the thermometer and thin film resistors are made following reduction of the heater current to zero. This happens immediately after taking the final data point at maximum temperature.

Since the thermal mass of the test structure is quite small, and since the unheated silicon is an extremely good heat conductor, removal of current causes an extremely rapid drop in temperature. Compare the rapid temperature drop shown in Figure 12 with the good part of an hour that a hot chuck without active cooling would take to return to ambient.

After the user selected time for temperature recovery has elapsed, the thermometer and resistor resistance values are re-measured. Default value for the delay time is one second. The resistor values are compared to the ambient values prior to the start of the temperature ramp.

Figure 13 shows the resistance response during cool down for the structure whose temperature response is shown in Figure 12. Note that the ordinate only spans a total of 600ppm, and that the rapid temperature decline is tracked by the thin film resistance change. However, it appears than some physical relaxation is occurring at a much slower rate since the thin film resistor is still 40ppm higher after 40 seconds than can be explained by temperature. Thus, if annealing or other physical changes occur within the thin film as a result of heating, it is necessary to have control over how long to wait for recovery.

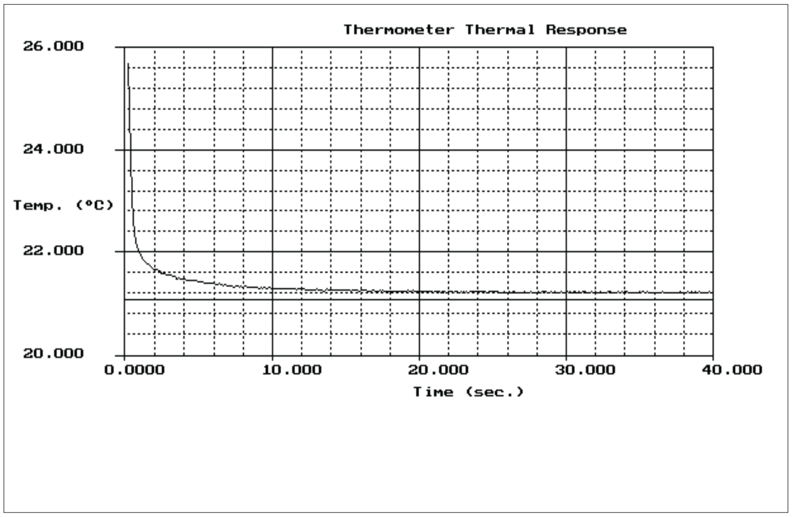

Figure 12 - Time Response of Temperature after Powerdown

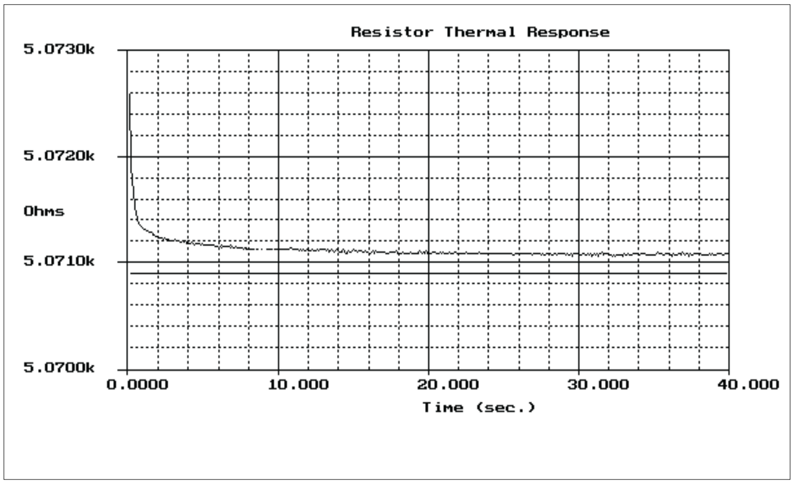

Figure 13 - Resistance Change after Powerdown