285°C Resistor Drift and Failure Analysis

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Abstract

In order to improve the reliability of down-hole electronics, Quartzdyne Electronics has invested millions of device test hours in life testing circuits in both powered and un-powered modes. In addition to time at temperature, these tests include thermal cycling and high impact drop testing. Resistors drift has become a significant wear-out mechanism in these tests. Prior testing has shown that resistor material, substrate material, resistance range and trim method each play a significant role in resistor stability at elevated temperatures. Some resistance ranges tested had no acceptable performers.

The purpose of this study is to expand the range of values, materials and package sizes in hopes of identifying reliable resistors for high temperature applications. This study will focus on a broad range of NiCr-on-silicon resistors, including larger package sizes than were previously tested. Additionally, we will be testing several precision foil-type resistors. Resistors will be mounted in hermetic packages and aged at 285°C for 1000 hours. The packages will be removed from the oven periodically and the resistance of the devices will be measured at ambient temperature. This study is being done in cooperation with resistor vendors who have supplied some of the devices for this test.

Keywords: High Temperature Electronics, Resistors, Aging, Drift, HALT Testing

Introduction

For over a decade, Quartzdyne Electronics has been testing circuit assemblies at elevated temperature to help qualify and improve the processes by which they are built. Two different tests are performed on production samples. The first, Life-Cycle, is a non-powered test of circuit assemblies that includes time at elevated temperatures, 15 thermal cycles to ambient temperature per week, and high-impact mechanical shock [1][2]. The other test (Powered Life) is of complete transducer assemblies, continuously powered and monitored daily while at a fixed maximum operating temperature.

These tests have become more severe as the circuits have improved. When hybrids were first introduced in Quartzdyne products eleven years ago, the target survival rate for the Life-Cycle test was 1000 hours at 200°C. Earlier tests did not include the high-impact shock [3]. The typical survival time of hybrid circuits made today is over 1 year at 250°C as shown in Figure 1.

Failures from the tests are analyzed to provide input for process improvements. With each improvement, the survival rate increases, and the next weak link is exposed. While most historic failure modes have been related to packaging, we are now seeing more component wear-out failures. Figure 2 reveals that resistor drift is one of two dominant end-of-life failure modes since 2006. The other is eutectic solder breakdown which was resolved in September 2008 with the introduction of our ASIC hybrid which eliminated the need for eutectic attach [4]. The ASIC hybrid is also less sensitive to resistor drift, resulting in increased circuit life with the same resistors.

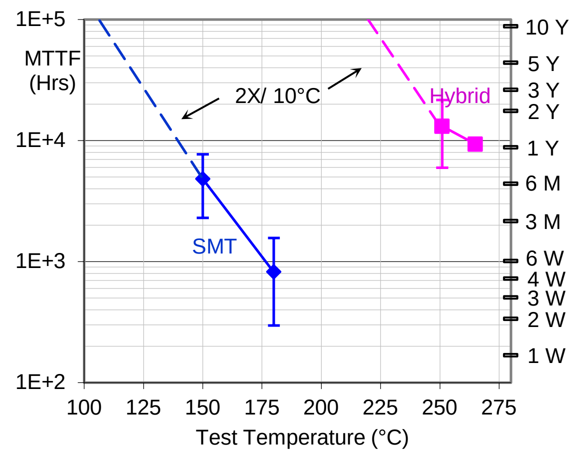

Figure 1. Mean survival rates in non-powered Life-Cycle test. Error bars at 10 and 90%. Graph includes Surface-mount (SMT) and Hybrid data from 2003 thru Mar 2011.

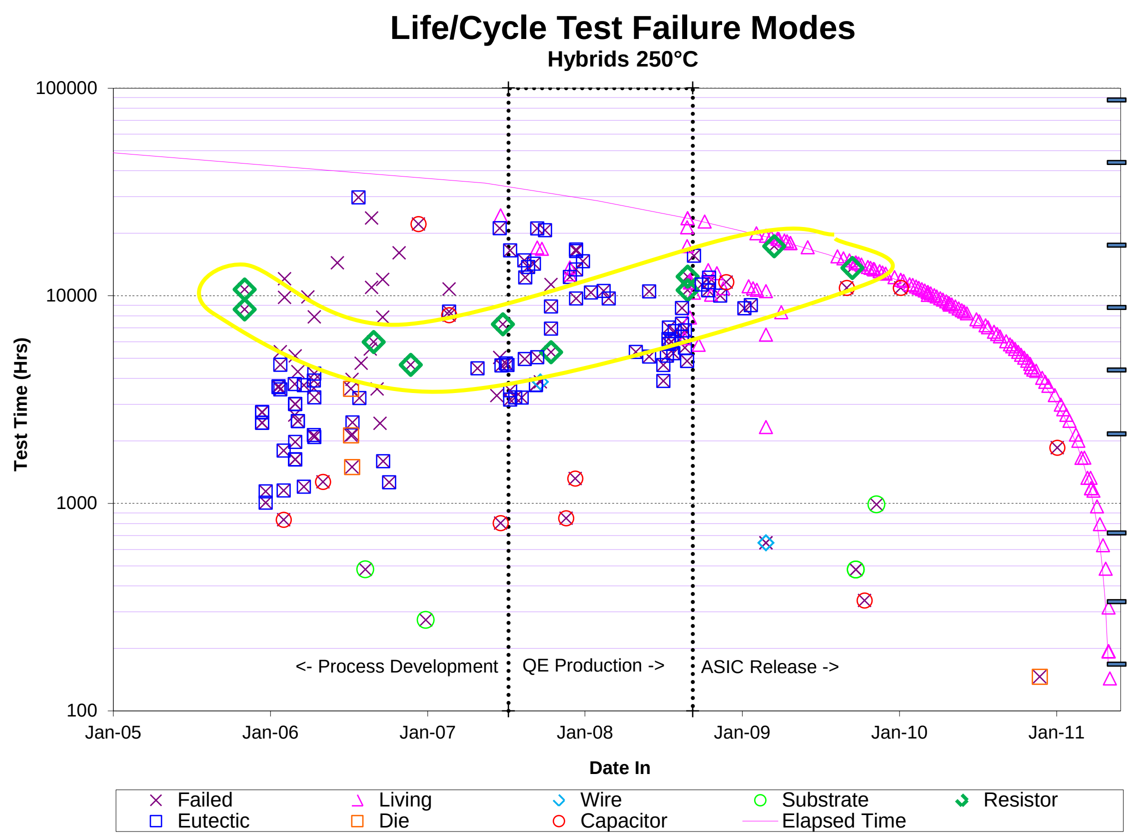

Figure 2: 250°C Life-Cycle test failures. Each symbol represents a circuit in the test. Surviving units generally follow the elapsed-time curve. Failed units are marked with an "X" and a failure mode. Early Eutectic and Substrate failures were from parts built while we were developing our in-house process. Eutectic was removed from the process in 2008 with the introduction of the ASIC models. Resistor Drift is now the dominant wear-out mechanism. Capacitors are also becoming a concern.

Resistor Aging Test Description

The resistor aging presented in this paper is a continuation of tests first reported at HiTEC in 2010 [5]. The prior work focused on thin-film Nickel Chromium resistors on Alumina substrates (NiCr/Al), but also included samples of thick-film Ruthinium Oxide ($Ru0_2$) and thin-film TaN resistors. In this work, the focus is on a series of NiCr-on-silicon resistors (NiCr/Si) designed specifically for high temperature applications [6]. Also included are several additional $Ru0_2$ thick-film resistors to fill in ranges that were omitted in the prior test as well as two Nickel-alloy current sense resistors (Table 1). Originally we had planned to include a series of precision metal foil resistors, but we were unable to acquire them in time for these tests.

Resistor package sizes include 0202 (.58x.58mm), 0505 (1.32 x 1.32mm), 0603 (0.9 x 1.8mm) and 0805 (1.25 x 205mm). Resistors were supplied with gold over nickel or aluminum wire-bond pads.

Six resistors of each value were mounted on a gold-plated alumina substrate at one end of a 14 pin hybrid package (Figure 3). One pad on each resistor was wire bonded to an I/O pad of the package, while the other was bonded to the substrate which was in turn bonded to the 7th I/O pin on each end. The packages were sealed with dry Nitrogen and then baked at 285°C unpowered. Units were removed from the test periodically and each resistor was measured through the package pins. Upon completion of the test the lids were removed and the resistors were re-measured directly on the die.

Table 1. Test Matrix: Bold values were tested in 2011. The remaining units were reported on at HiTEC 2010. The NiCr/Si resistors are separated into two groups by vendor.

Technology	Values Tested
Ni/Al	**0.1, 0.5**
NiCr/Al	750, 4.75k, 15k, **63.4k,** 249k
NiCr/Al-NT	250, 750, 4.5k, 15k, 550k
NiCr/Si(A)	330k, 499k, 830k
NiCr/Si(B)	**33, 1k, 10k, 27.4k, 100k, 200k, 450k, 499k, 750k, 1M, 2M**
RuO_2/Al	49.9, 750, 4.75k, 15k, **200k,** 249k, **270k, 374k, 470k, 1M, 2,2M**
TaN/Si	820, 5k, 14k, 432k

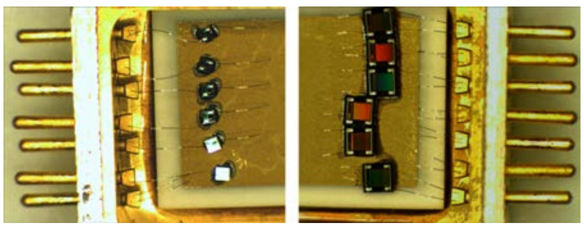

Figure 3. Resistors placed in ends of hybrid package with contacts bonded to I/O pins for testing. Resistors share a common ground pin.

Test Results

Test results for the thin-film NiCr/Al and thick-film RuO_2 were similar to results from the prior test [5]. As seen in Figure 4, the 63.4k Ω NiCr/Al aged approximately 4% over 1000 hours. The prior test showed a wide lot-to-lot variation with units aging from 2% to 15% under the same conditions.

The thick-film RuO_2 resistor aging was also highly variable. As shown in Figure 5, the 270k and 470k units were respectable with 1.5 and 2.5% aging, but most other units in the same range aged between 5-10% (Figure 6). Unit-to-unit variation within a lot was good, but was not as tight the NiCr/Al units. These resistors could be adequate for low-precision applications where, for example, the surge handling advantage of thick-film resistors is important.

Careful observation will show that some data points are missing from the graphs. Several of the resistors measured open circuit at some intermediate points. Upon opening the packages it was discovered that the substrates had not been properly attached to the packages and had shifted during the test, breaking some wire bonds. All resistors were measured directly on their bond pads after the packages were opened and both the through-pin and direct-do-die measurements (without wire bonds) are plotted at the 1000 hour point.

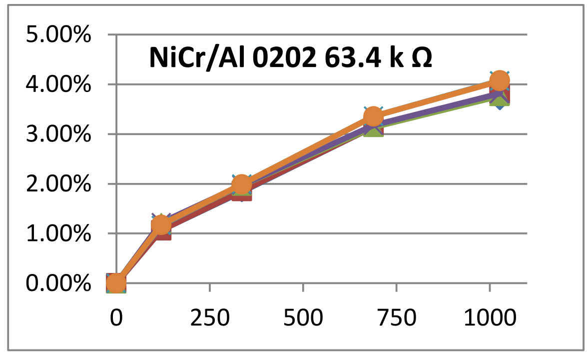

Figure 4. NiCr/Al 63.4kΩ: The smooth exponential aging characteristic is typical of similar units in prior test. Individual units track each other well.

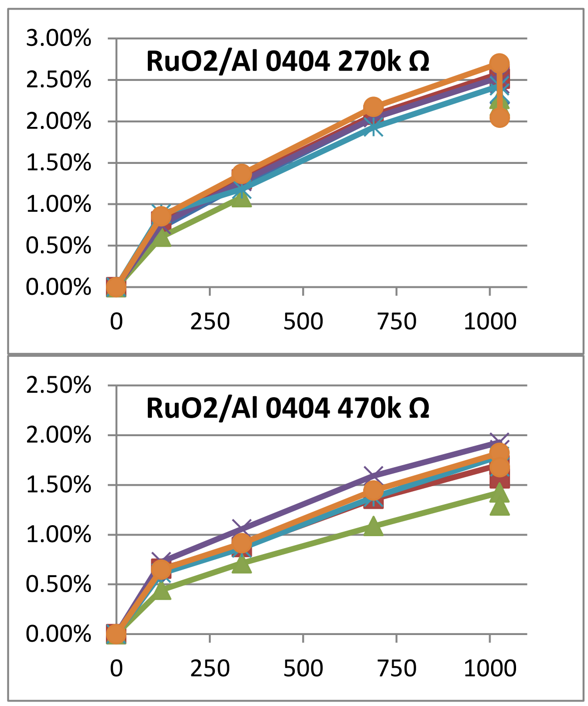

Figure 5. Thick-film RuO_2 resistor aging. These particular units performed well, but are not typical of other resistors from the same family.

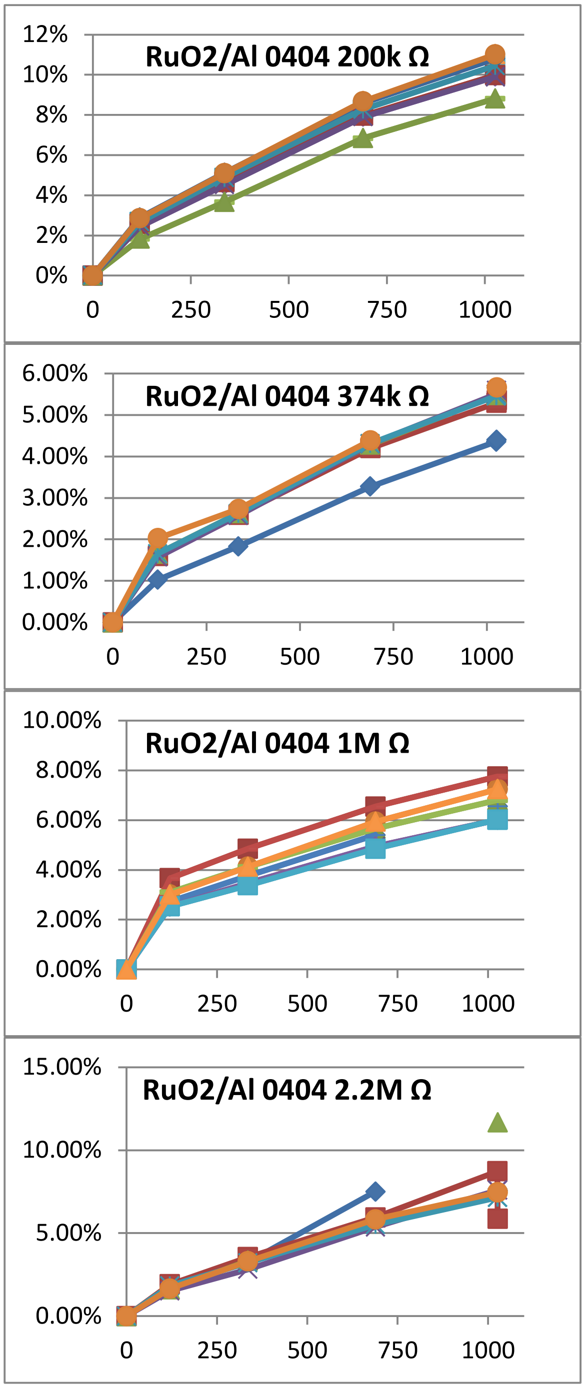

Figure 6. Thick-film RuO_2 resistor aging: Drift ranging from 5-12% is higher than we would like to see, but may be acceptable for non-critical applications.

The NiCr/Si resistors performed exceptionally well in our tests with typical aging on the order of +/-0.3% as shown in Figure 8 and Figure 9. Aging was both positive and negative, with several values changing direction over the course of the test. No significant differences were noted between the various ranges, nor was package size significant (compare 450k and 499k with 0505 and 0202 packages respectively). We have no explanation for the two outlier points on the 1kΩ resistor. The readings were repeatable, and independent of wire bond impedance.

The performance of the NiCr/Si resistors is a full order of magnitude better than the NiCr/Al group. We also tested three high-value NiCr/Si resistors from a different vendor that performed poorly. Clearly, differences between the specific formulations and how they are processed are more critical than the class of resistors

The prior testing [5] demonstrated the significance of trimming. Damage to the resistive element near the trim site provides opportunity for crack propagation resulting in increased resistance over time. Another possible difference between the NiCr/Si and the NiCr/Al could be surface finish. Thin films deposited on the rougher alumina surface may have more opportunity for instability than on the polished surface of single-crystal Silicon.

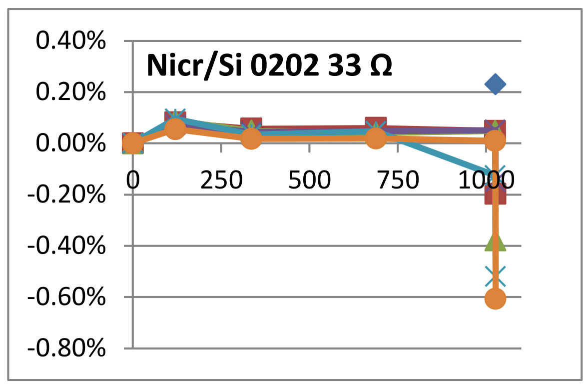

Figure 7. 33 Ω NiCr/Si resistor showing good stability over time at 285°C, but a significant difference between through-wire bond and direct-on-die impedance after 1000 hours.

In Figure 7 we see that the performance of the 33Ω resistor is similar to that of the other NiCr/Si resistors except that the final readings without wire bonds out of line. This is due to two different factors. First, the combined wire bond impedance of approximately 0.15 Ω is significant (0.5%). Second, the probe contact impedance is highly variable when contacting the die directly. These units were probed by hand with a microprobe. Permanent damage to the bonding pad occurs as the probe makes contact. Probe contact angle and applied force are variables. Given the small bond pad size, 4-wire measurements were not possible on these resistors with the available equipment.

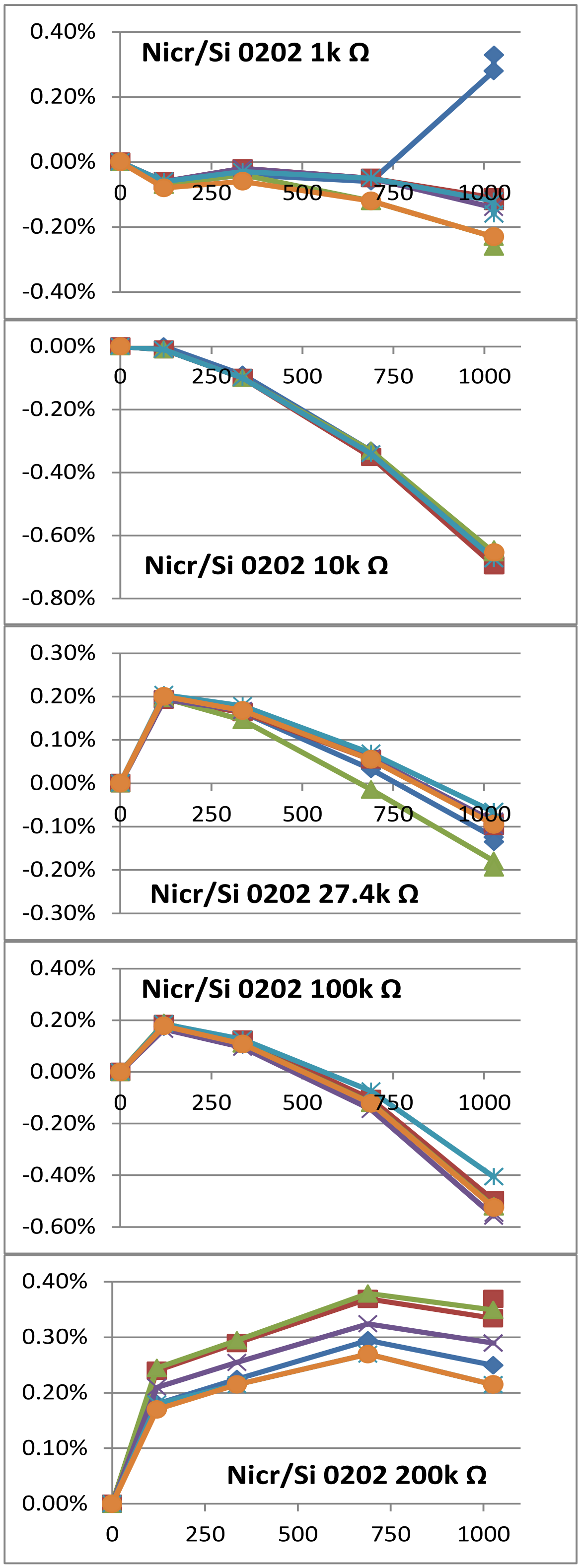

Figure 8. NiCr/Si resistors showing excellent aging performance over 1000 hours at 285°: The outlying point on the 1k Ω resistor is repeatable.

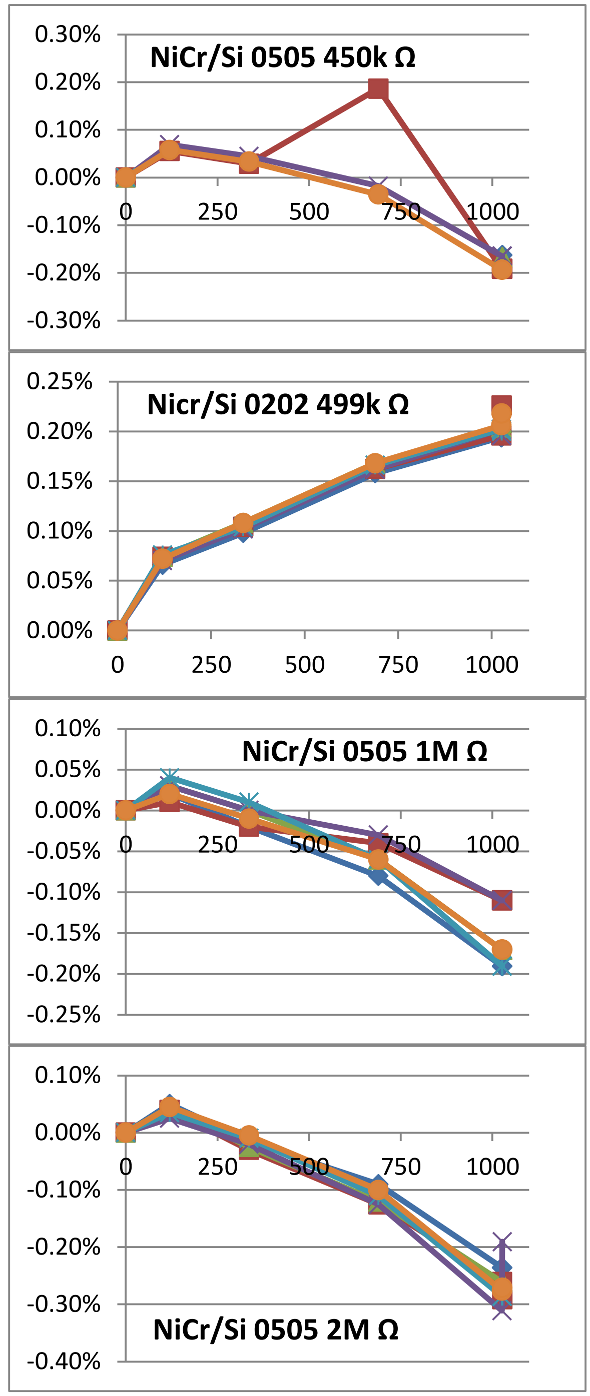

Figure 9. NiCr/Si resistors showing excellent aging performance over 1000 hours at 285°: The outlying point on the 450kΩ resistor is likely a measurement error. No significant difference is observed when comparing package sizes (0202 vs. 0505).

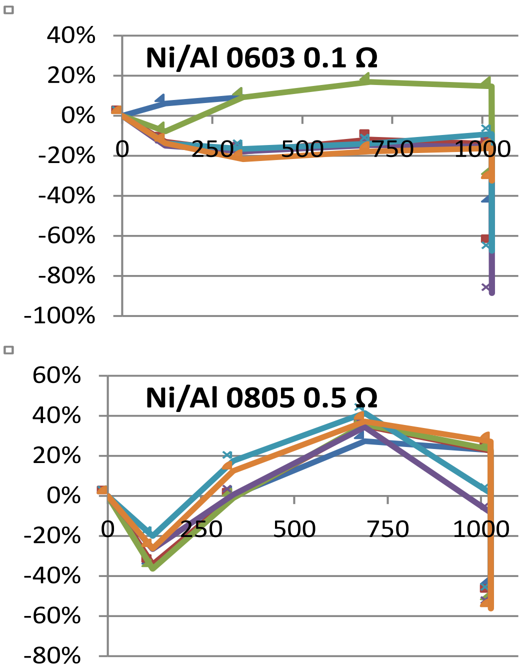

Figure 10. Nickel alloy current-sense resistors: Aging is erratic with significant contribution from wire bond impedance.

Nickel alloy current sense resistors

Two low value Nickel-alloy-on-alumina (Ni/Al) current sense resistors were included in this test. These were tested in the same method as the other resistor through wire bonds and package I/O pins using 2-wire resistance measurements. In retrospect, a 4-wire test setup would have been more appropriate. The plots in Figure 10 show poor performance.

Additional testing was done to try to separate the actual resistor drift from the wire-bond contribution. New and aged resistors were measured using a 4-wire setup. The 0.1 Ω resistors were in tolerance initially, but measured 0.05 Ω after aging indicating a 50% drop from the nominal impedance. The 0.5 Ω resistor showed a similar 50% reduction in value when aged. Typical wire bonds were measured 0.13 Ω un-aged, while the aged bonds measured closer to 0.15 Ω – a 0.02 Ω increase.

Note that the wire-bond drift was in the opposite direction of the resistor drift. Considering three wire bonds in series with each resistor, we would expect the 0.1 Ω to have a beginning and final reading of 0.49 and 0.5 Ω respectively for a final reading total reading of +2%. By the same argument, the 0.5 Ω resistors should have shown measured 0.89 Ω initially, and 0.7 Ω at the end for a -27% net change. This does not agree with what we see in the graphs, reducing our confidence in making firm conclusions about these resistors.

Resistance versus Temperature

Two resistors were measured at various temperatures between 25°C and 285°C to determine the temperature coefficient of resistance. Both had reasonable performance as shown in Figure 11. The outlying point on the 63.4k Ω resistor is likely in error. The probe was adjusted shortly after the reading was taken and the remaining points were more reasonable. We did not have time to repeat the test. The performance of either resistor is equal to or better than its aging performance and would be considered adequate for our application.

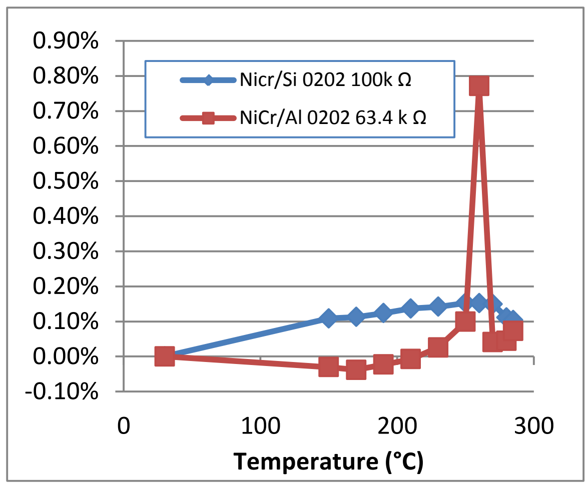

Figure 11. Resistance change over temperature: The 260°C point for the 63.4k Ω resistor is likely in error. The probe was adjusted prior to the reading at 170°C.

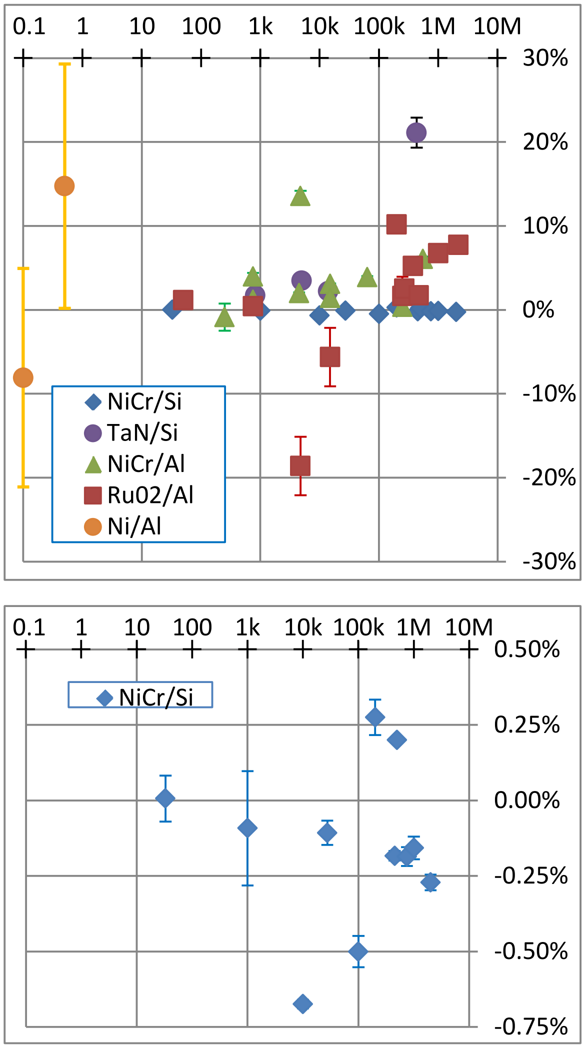

Figure 12. Drift after 1000 hours at 285°C with error bars at +/-1 standard deviation: NiCr/Si is plotted separately on the second chart with a tighter vertical scale.

Performance Summary

Figure 12 shows the performance for each of the tests done both in this work and the prior HiTEC 2010 paper [5]. I-bars are shown at +/- one standard deviation to indicate the relative tracking of units within the same test. The second chart shows the performance for just the NiCr/Si group on an expanded scale.

The performance of the high temperature NiCr/Si resistors was excellent across the entire range with aging less than 1% after 1000 hours at 285°C. NiCr/Si from Vendor A did not perform as well in the prior tests indicating differences between manufacturers are more significant than the class of materials used. Where thick-film is required, expect aging on the order of 10% with high variability from lot-to-lot. It appears that the Nickel alloy resistors have a significant negative drift (50%), but given the uncertainties in the measurements, further testing will be required before giving a final verdict on these.

Acknowledgement

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