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 over 10 million device test hours in life testing of our circuits in both powered and un-powered modes. In addition to time at temperature, these tests include thermal cycling and high impact drop testing. While resistors tend to be generally reliable, we have observed resistance drift in some units that has pushed circuit performance outside of accepted electrical specifications. In an attempt to comprehend the root cause(s) of resistance drift, failed samples have been studied in a scanning electron microscope. The resulting observations have led to structured designs of experiment to isolate the many possible root causes. This paper will present these observations, experimental outcomes and draw conclusions surrounding thick film vs. thin film performance, variations between value ranges, differences between vendors, and a possible link relating the drift mechanism to the method and extent of value trimming. This information should be useful to resistor vendors interested in improving the quality and performance of their products.

Keywords: High Temperature Electronics, Resistors, Aging, Drift

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 ten 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 6 months at 250°C including 100 impact tests and 800 thermal cycles as shown in Figure 1. The figure also shows data for surface mount (SMT) assemblies for reference.

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 starting to see more component wear-out failures. Figure 2 reveals that resistor drift has become one of two dominant end-of-life failure modes. The other is Eutectic Solder Breakdown which was resolved in 2009 by eliminating the devices that required eutectic solder [4]. We embarked on this study to determine what, if anything could be done to improve resistor performance. All resistors are supplied with 1% tolerance. Our circuit is sensitive to drift of 5%.

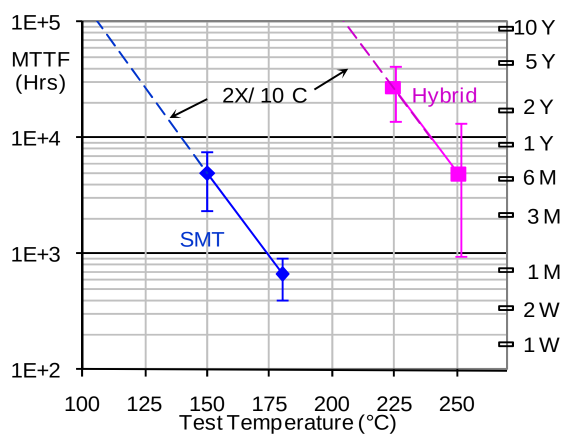

Figure 1. Mean survival rates in non-powered Life-Cycle test. Error bars at 10 and 90%. Graph includes Surface-mount (SMT) and Hybrid data from 2003 thru Feb 2010.

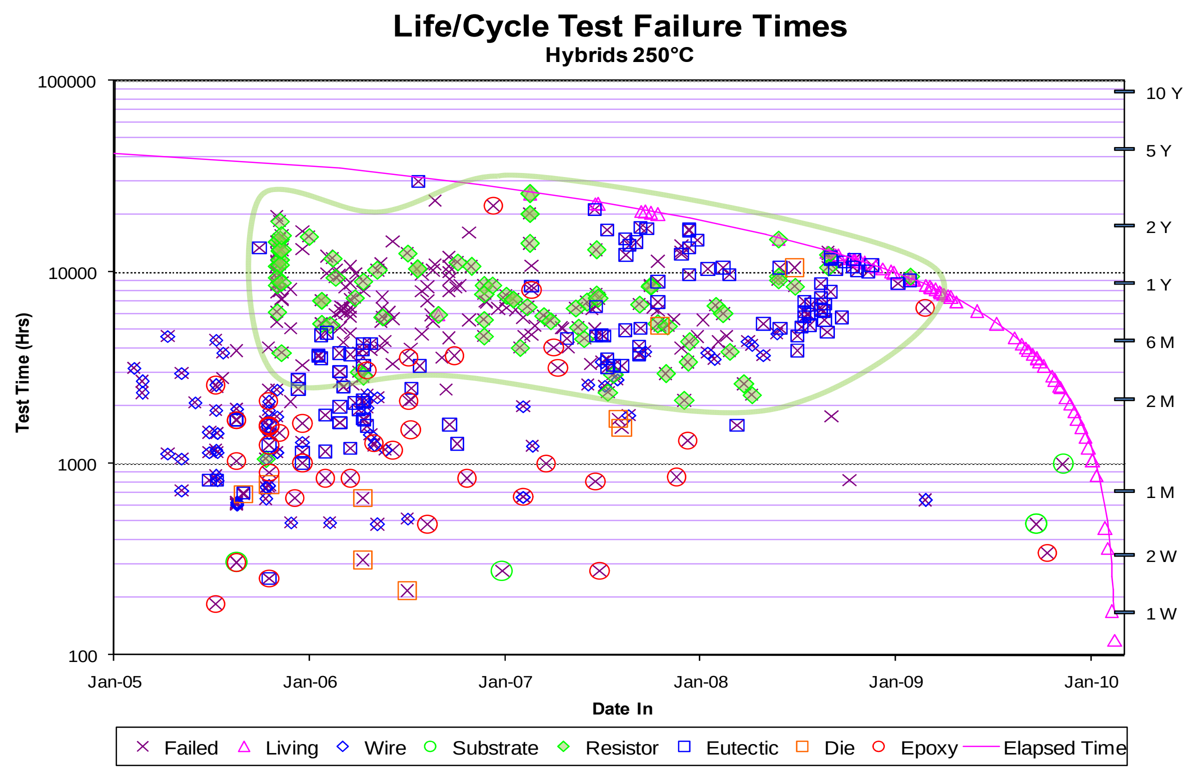

Figure 2: 250°C Life-Cycle test failures. Each symbol represents a circuit in the test. Surviving units follow the elapsed-time curve. Failed units are marked with an "X" and a failure mode. Early Wire-bond, Die, and Epoxy failures have been addressed and no longer dominate. Eutectic was removed from the process in Jan 2009. Resistor Drift is now the dominant unsolved wear-out mechanism.

Test Description

Five separate tests were run to characterize resistors now used in production which had shown failures in our Life-Cycle testing. Alternative technologies were also included in hopes that an improved offering could be found. The tests are summarized in Table 1. Plots of all resistor drift are included throughout the paper.

The first test included three types of wire-bondable resistors: thin-film NiCr on Alumina (typical of those used in our standard products), thin-film NiCr on Silicon and Tantalum Nitride on silicon. The resistors were mounted to a larger ceramic substrate with no wire bonds. They were baked in a convection oven at 285°C while fully exposed to air. Data was taken at 0, 300, 600 and 900 hours. Resistors were measured by directly probing the bond pads.

Table 1: Resistor aging test matrix. All units are thin-film wire-bondable except as indicated. See text for additional details.

Test	Technology	Values	Hours 250°C	Hours 285°C	Tot Qty
1A	TaN/Si	820, 5k, 14k, 432k		900	40
1B	NiCr/Al	750, 4.75k. 15k. 249k		900	40
1C	NiCr/Si	499k, 330k, 830k		900	30
2	NiCr/Al-NT	250, 750, 4.5k, 15k, 550k		1000	25
3A	NiCr/Al	49.9*, 750, 4.75k, 15k, 249k	1350	1100	10
3B	NiCr/Al-ET	49.9*, 750*, 4.75k*, 15k*, 249k*	1350	1100	30
4A	NiCr/Al	49.9*, 750, 4.75k, 15k, 249k		2100	10
4B	NiCr/Al-ET	49.9*, 750*, 4.75k*, 15k*, 249k*		2100	30
5	NiCr/Al	49.9*, 2.49k, 1.5k, 15k, 24.9k, 20k, 499k, 100k, 47.5k	5249		34
	**Thick-Film Resistor*				
	Total Device Test Hours		**60741**	**46900**	**249**

The second test was NiCr on ceramic, but in this case they were supplied from the factory untrimmed in order to separate trimming as a variable. This test was also done at 285°C and data was taken at 0, 125, 300, 600 and 1000 hours.

The 3rd and 4th tests introduced thick-film RuO_2 resistors with wrap-around end terminations.

Also included in these tests, as a control group, were wire-bondable NiCr resistors as had been tested in the first test and two values of wire-bondable thick-film RuO_2 resistors that are used in our standard product. The resistors in these tests were mounted on a ceramic substrate and then sealed in a Kovar package with Au wire bonds to external leads. Each device was measured directly on the bond pads before the test packages were sealed. Bond wire and probe resistances were measured at the beginning and end of the tests and were deemed insignificant relative to the aging affects observed.

Test 3 units were aged for 1350 hours at 250°C and then moved to the 285° oven for an additional 1100 hours. Test 4 units were tested at 285° for 2100 hours. Resistance was measured about every 330 hours during the tests.

The fifth test was a production unit that failed for resistance drift after 5400 hours at 250°C in the Life-Cycle test. This unit was opened, and all 34 resistors were probed and compared to their nominal (1%) values.

Observations from the Data

The measured drift in the thin-film resistor samples is generally positive, and very consistent from unit-to-unit within a specific value. NiCr showed an exponentially decaying drift (Figure 8), while the TaN drift was more linear (Figure 4). Units aged first at 250°C and then at 285°C showed dual-exponential patterns as might be expected (Figure 9). Surprisingly, the drift in some of the resistors changed direction during the tests (250Ω NiCr/Al-NT, 249kΩ NiCr/Al, 249kΩ NiCr/Al-NT and 499kΩ NiCr/Si). Unit-to-unit variation was greater with the large and small-valued devices than with the mid-range thin-film resistors.

Thick-film resistors were more likely to drift negatively (Figure 9 and Figure 10). The lower values performed well with drift under 2%, mid-range values had the high-negative drift (5% to 28%) and the high-value 249kΩ showed offsetting positive and negative drift. Figure 6 shows a low-drifting 50Ω and a high-drifting 4.75kΩ resistor. The edge definition is tighter on the 50Ω device.

The drift within a single value of any of the technologies is surprisingly consistent. Most have standard deviations less than 1%. Lot-to-lot variation was observed with 15k NiCr resistors from two different lots from the same vendor. The variation of drift magnitude from value-to-value within a technology was surprisingly erratic, several values drifted less than 3%, while others of the same family drifted 10-20% (Figure 4 and Figure 5).

An SEM of some of the high-drifting NiCr/Si devices revealed anomalies in the trim-area (Figure 3). This prompted testing of un-trimmed resistors as a follow-up (Test 2). The mid-range untrimmed values in this 2^{nd} test (Figure 8: 750Ω, 4.5kΩ and15kΩ) showed very low drift compared to their trimmed counterparts suggesting that the method or quality of trimming is significant.

In general, drift on resistors with plunge-cuts into a large bulk region was much worse than drift on resistors that had been trimmed by ladder-rung cutting (Figure 11). If the plunge trim cut was initially partially conductive, cracking or diffusion of the adjacent material could explain the increase in resistance observed during the tests.

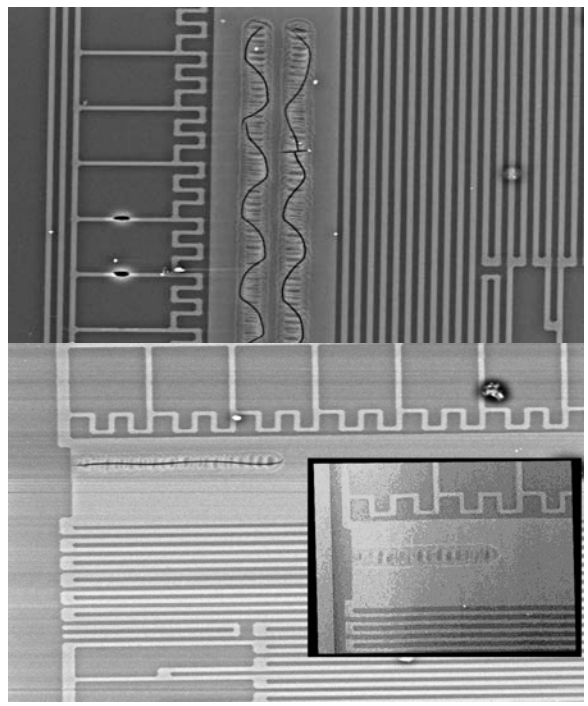

Figure 3: SEM of 830kΩ NicCr on Silicon resistors showing serpentine cracks in the trim area after aging. The inset in the lower picture shows that these cracks were not present at the beginning of the test.

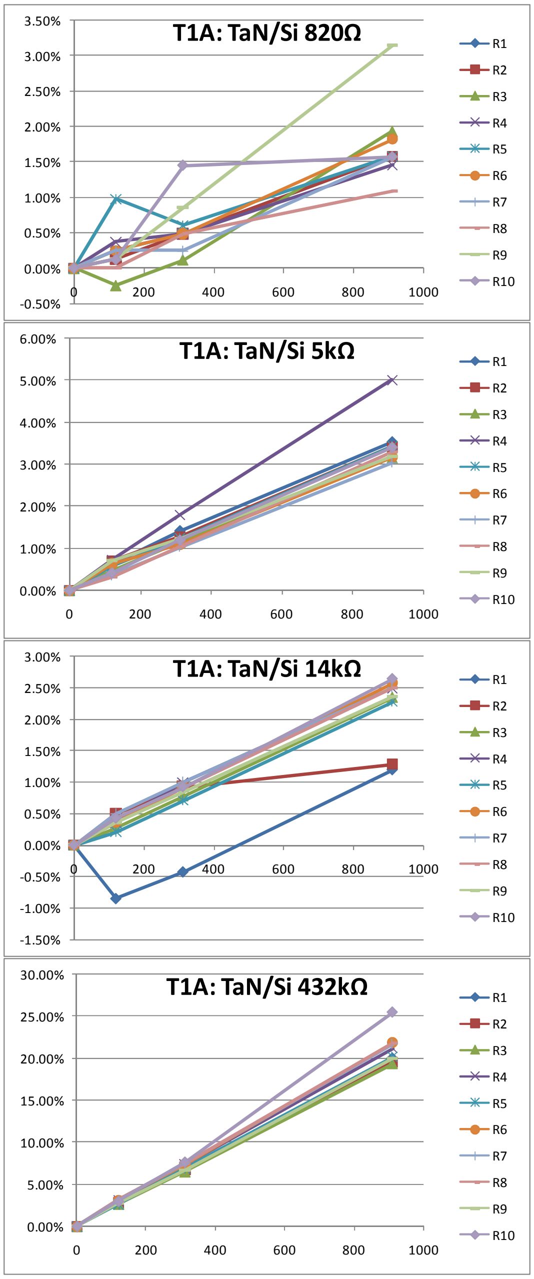

Figure 4: Test 1A - Tantalum Nitride on Silicon aged for 900 hours at 285°C. Drift is mostly linear, but several outliers cause concern. Note the high drift rate on the 432kΩ resistor.

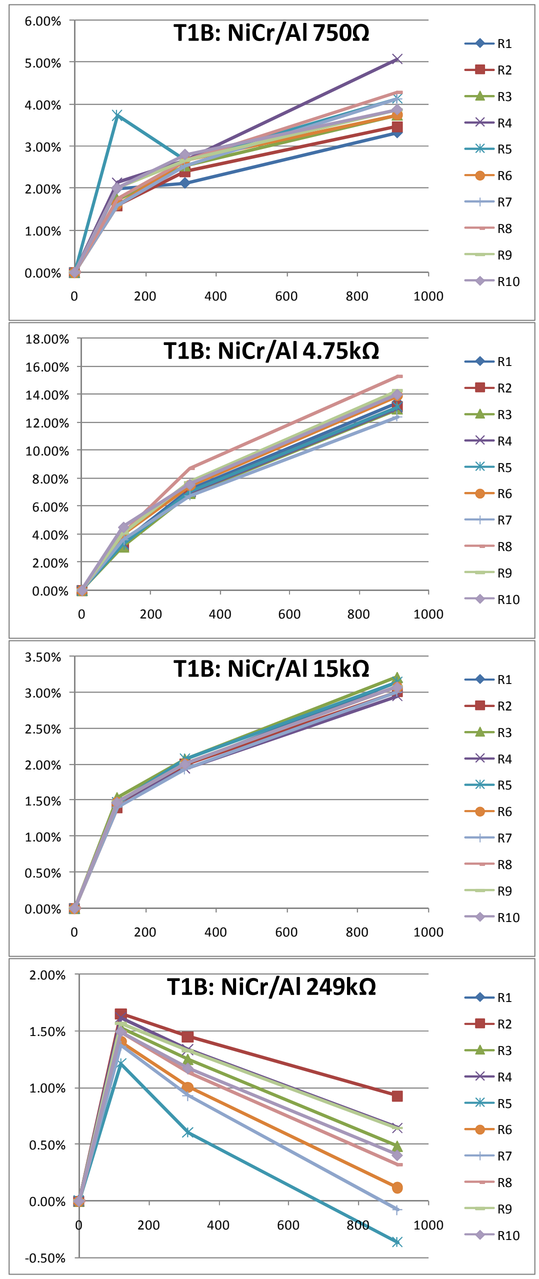

Figure 5: Test 1B - NiCr on Alumina tested for 900 hours at 285°C. Exponential decay of drift rate is typical. Note bi-directional drift on 249kΩ and large magnitude on 4.75kΩ.

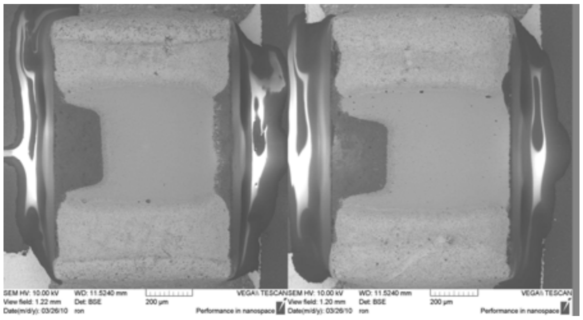

Figure 6: Thick film RuO_2/Al end-terminated. 4.75kΩ on left drifted -20% while 49.9Ω on right drifted +2%. Note the poor edge definition on the right side of the left resistor.

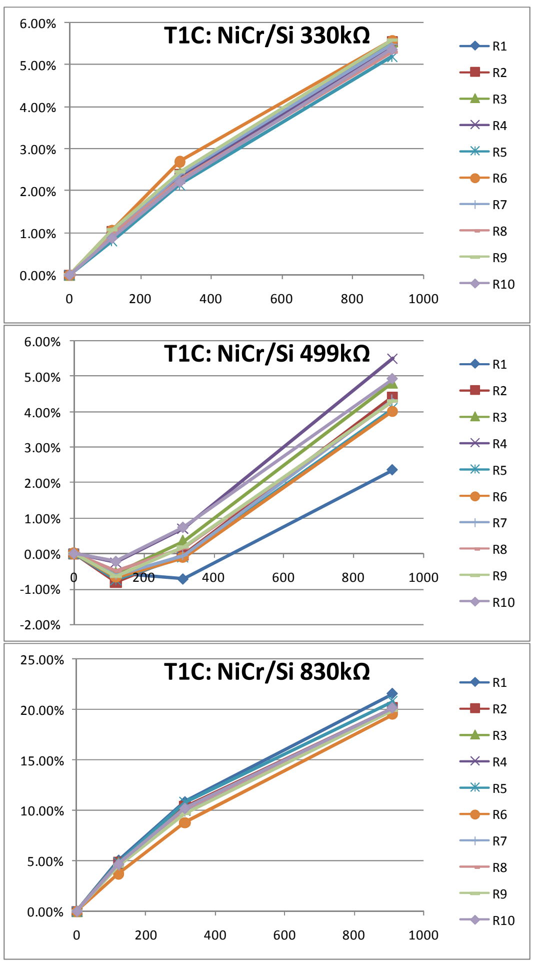

Figure 7: Test 1C - NiCr on Silicon. Note the turn-around in drift on the 499kΩ resistor and the high magnitude on the 830kΩ.

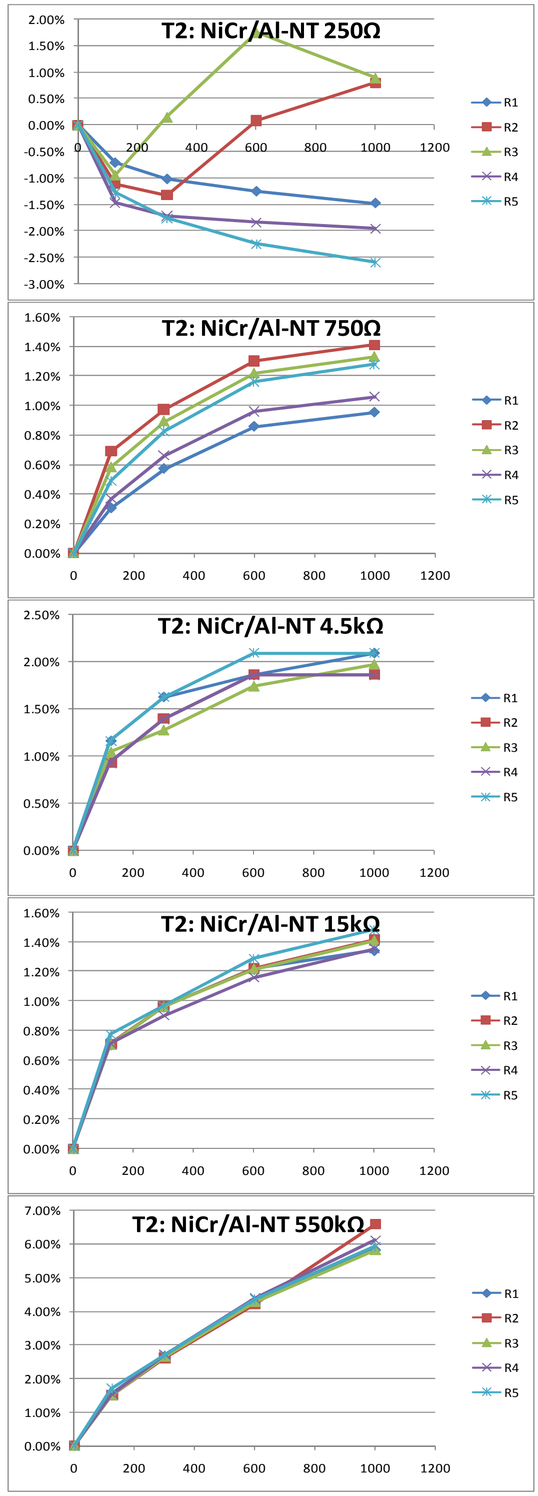

Figure 8: Test 2 - NiCr on Alumina untrimmed. Drift is excellent on all but the 550k resistor. Note the inconsistent drift of the two outlying 250Ω resistors.

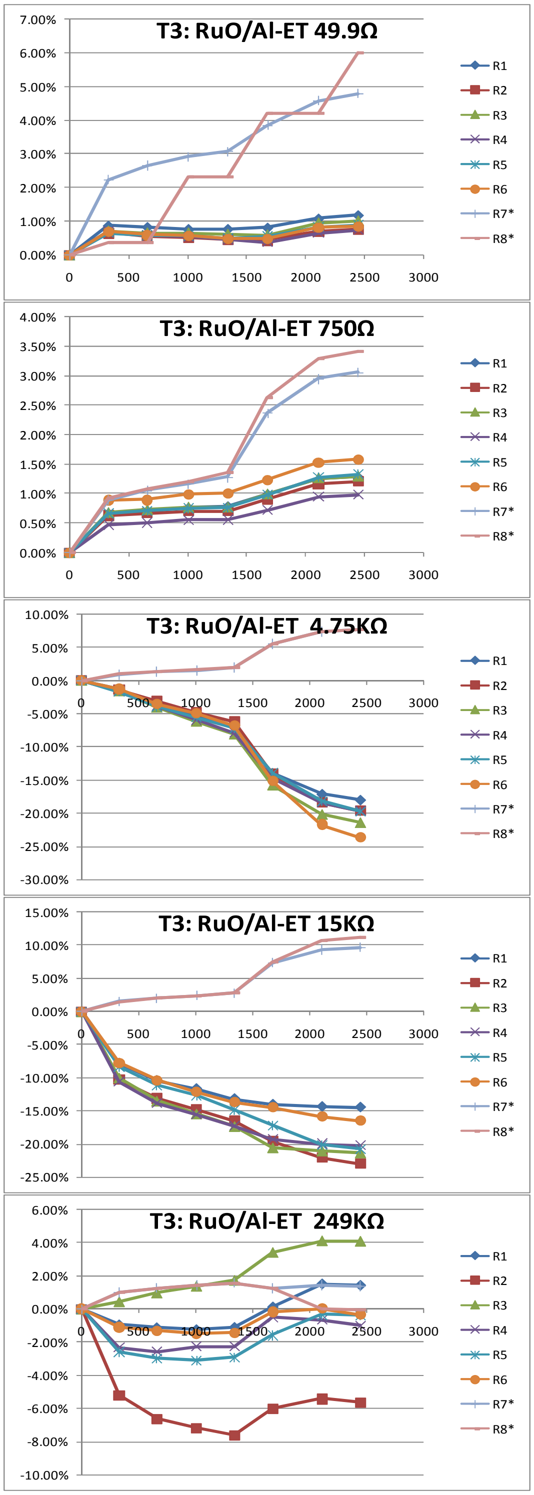

Figure 9: Test 3 - SMT style end-terminated RuO_2/Al thick film resistors. These were initially aged at 250°C for 1350 hours, followed by 285°C for 1100 hours. R7* and R8* are wire-bondable NiCr resistors for comparison.

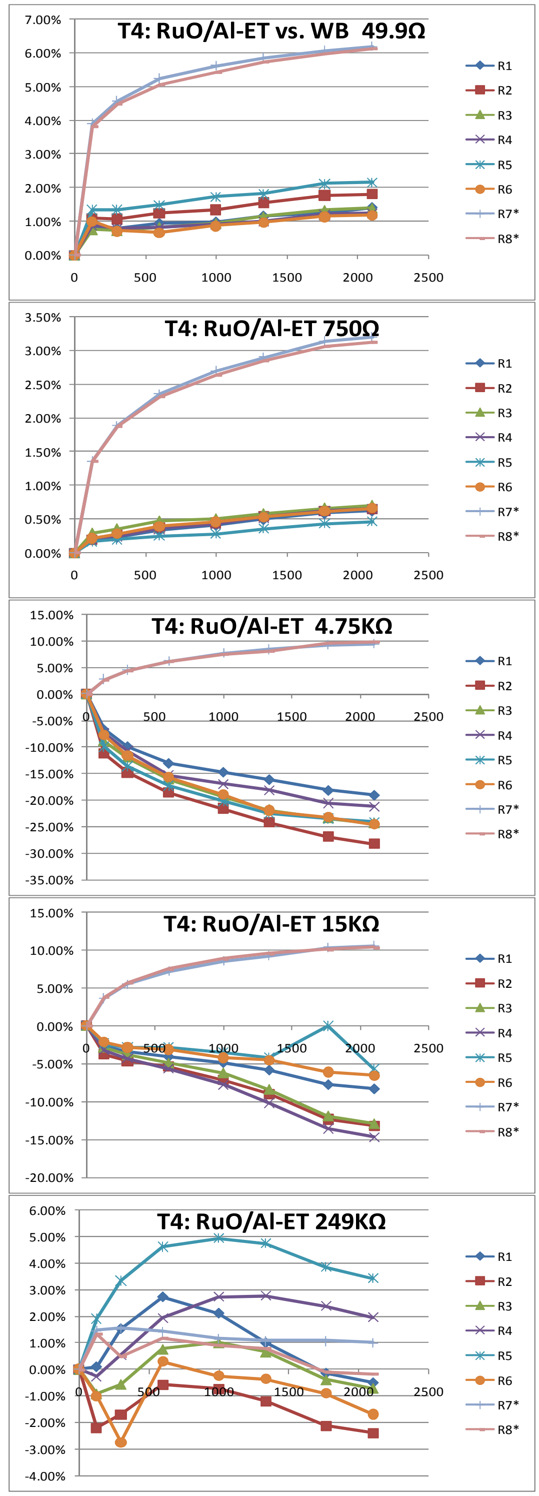

Figure 10: Test 3 - SMT style end-terminated RuO_2/Al thick film resistors. Units were aged at 285°C for 2450 hours. R7* and R8* are wire-bondable NiCr resistors for comparison.

Low-valued resistors (49Ω to 1kΩ)

Only thick-film 50Ω resistors were tested. Thin film versions were excluded from our design several years ago because of ESD sensitivity. The end-terminated samples performed much better than their wire-bondable counterparts (2% versus 6% as shown in Figure 9 and Figure 10).

Between 100Ω and 1kΩ, all candidates performed within our required +/- 5%. One notable anomaly was the 250Ω NiCr/Al resistors where three of the five resistors drifted negatively, while two took a significant positive jump after 150 hours (Figure 8). As with the 50Ω resistors, the best performers in this range were the end-terminated thick film resistors (0.5 to 1.2%)

Mid-range values (1kΩ to 100kΩ)

The end-terminated thick-film RuO_2 resistors in this range all drifted greater than -5%, with most drifting -10 to -20% (Figure 9 and Figure 10). The untrimmed thin-film NiCr/Al resistors were the best, with drift in the 1% to 2% range (Figure 8). Close behind were the TaN resistors with typical drift of 2% to 3% after 900 hours at 285°C. These were tightly bunched except for 1 or 2 outliers in each group (Figure 4).

Drift of the trimmed NiCr/Al resistors in the study was generally bad. There was high variability from value-to-value and lot-to-lot, with drift ranging from 3% on the low end to 11% on the high end. Given the great performance of the un-trimmed versions of the same, we see this is the biggest opportunity for vendor improvement.

High-valued resistors (>100kΩ)

Performance was generally poor for resistors greater than 100kΩ. Most resistors had bi-directional drift with typical drifts in the +/-5% range. The best performers were the 249kΩ thin-film NiCr/Al resistors (Figure 5), with worst-case drift of +1.7/-0.4%. In contrast, and counter to the trimming results in the prior section, the 550k un-trimmed thin-film NiCr/Al 550k resistors were significantly worse at -6% (Figure 8).

Drift on the 249kΩ *thick*-film resistors was bi-directional with high variance. Some units drifted net positive while others drifted negative, the net drift ranging from -5.6% to + 4.2% (Figure 9 and Figure 10). The 499k thick-film resistors showed similar performance, with complex drift and high variance unit-to-unit.

The worst of the high-value units were those on Si substrates which showed drift as high as 25% in 2000 hours at 285°C. The NiCr/Si units showed peeling of the top layer in the area of the plunge-trim (Figure 3). The 432k TaN/Si group showed 20% drift. Based on this test result, we have concluded that Si is not a good choice for high-value resistors for high temperature applications. Given the limited sample and inconsistent performance, the choice between thin or thick film is not as obvious.

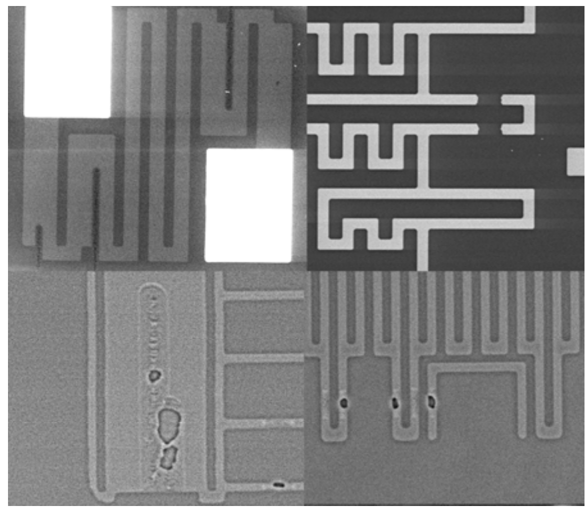

Figure 11: Comparison of trim methods. Top Left is a plunge-cut 15k NiCr resistor that drifted 10%. Top-right is a 14k TaN resistor with ladder trimming which drifted 2%. The 330k NiCr resistor on the bottom has both plunge and ladder trims which both appear to be incomplete or non-uniform. Its drift was 5.5%.

Comparison with Life-Cycle

Two components in the Life-Cycle test sample had corresponding components in the 285°C tests. Resistor drift in Life-Cycle testing for the 49.9Ω thick-film resistors after 5400 hours at 250°C was comparable to drift on the corresponding test group after 2100 hours at 285°C (6.2%). The comparison of the 15kΩ resistors is not as good. The Life-Cycle unit drifted the same as the non-trimmed group (1.2%) while the trimmed test units drifted approximately 10%. The 7% drift of the 25kΩ resistor in the Life-Cycle test compares better to that of the 10% drift of 15kΩ resistors in the other tests.

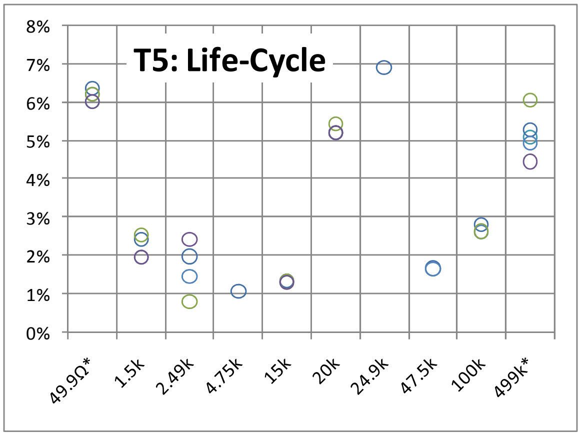

Figure 12: Drift of resistors in Life-Cycle test sample after drift 5249 hrs at 250°C. Test also included approximately 500 thermal cycles to 25°C. All resistors are thin-film NiCr/Al except for the RuO_2 thick-film values noted with an asterisk (*). The 5% drift on the 20kΩ resistor caused the circuit to fail.

On average, drift of the thin-film NiCr/Al resistors in the 250°C Life-Cycle group was one quarter to one half that of the 285°C tests indicating a more aggressive de-rating factor than the thick-film. Consistency is not sufficient to calculate the activation energy.

The data would suggest that lot-to-lot variation is a key factor in the amount of drift to be expected. Life-Cycle failure patterns also support the lot-to-lot variation theory as both the specific failed value and the density of resistor drift failures varies over time. Given the tight comparison from unit-to-unit within a lot, lot sorting could be a viable option for critical applications.

Conclusions

It is difficult to make specific conclusions regarding the results of this test with any degree of confidence. The test was a relatively broad sampling of parts and technologies, and no clear winners were found. Given the variability of results within a technology it is not clear that testing of more lots would do anything more than confirm the level of inconsistency already observed.

For low-valued resistors the end-terminated thick film RuO_2/Al performed well, but at higher ranges this technology was unacceptable. In the mid-range, un-trimmed or sorted thin-film NiCr/Al resistors are preferred. The TaN/Si resistors in this range were more consistent, but outlying units and the non-saturating linear drift are concerns. For high values, Silicon is not a viable substrate option. The data on thick-film versus thin-film is non conclusive, and the bi-directional and highly variable nature of the drift makes lot sorting ineffective.

As consumer of resistors for critical high-temperature applications, we are at the mercy of the few vendors willing to supply us parts. It is our hope that the problems exposed in these tests will spawn additional tests and possible improvements by vendors wishing to supply components to this difficult market.

Table 2. Summary of test results after 1000 hours at 285°C. No single technology performed well in all tests. Lot-to-lot variation was evident in trimmed resistors

	50 250	500 2.5k	5k 25k	50k 250k	300k 820k
Thick-RuO_2/Al	6%				
Thick-RuO_2/Al-ET	2%	2%	5% / 20%		
Thin-NiCr/Al		2% / 5%	2% / 15%	3%	
Thin-NiCr/Al-NT	2%	2%	2%		6%
Thin-NiCr/Si					5% / 20%
Thin-TaN/Si		2%	3%		20%

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