Predictable Components: Stability of Thin Film Resistors

ABSTRACT

The dream of many application and quality engineers is to be able to predict with high accuracy the reliability of an electronic circuit. A good example was the project of the "Rome Air Development Center" which aimed to collect, analyse, and interpret reliability data on components in the form of mathematical equations, in order to be able to make a statement regarding the reliability of an equipment. The attempt has, in most cases, failed due to the fact that many components show early defects, and their ageing behaviour and failure mechanisms were not available with sufficient precision.

Generally, the specifications of thin film resistors are fixed by maximum load and temperature for 1000 h. The detailed resistor specifications of CECC give stability classes for special resistive values. But how will those components behave when temperatures or loads are different, or circuit lifetime should exceed 1000 h? Is it possible to promise, or expect, higher stability when certain applications require it?

Thin film resistors are very well defined components and their ageing mechanism follows special physical rules. They can be described by the Arrhenius' equation.

New investigations have shown that the behaviour of thin film layer systems are different and specific. The stability depends on both the special manufacturing process, and on the resistive layer system too. In consequence, the stability of metal film resistors can be influenced by a factor of 2 to 5.

The paper will describe the influences on the stability of thin film resistors and the findings by using Arrhenius' equation will be discussed. It will be shown that it is possible to predict typical ageing behaviour of different resistive layer systems by a derived equation valid for the whole temperature-time-expanse relevant to electronic applications. Improved thin film resistors follow well-defined "paths of stability" when related to Arrhenius to characteristic numbers.

WHY IS STABILITY OF RESISTORS RELEVANT?

Approximately 40 % to 50 % of components in an electronic circuit are resistors. They are the most common components in electronics but, in terms of the value of a typical circuit, they represent only 2 % to 5 % of the total. So it is not surprising that design engineers are not very interested in those "simple" components. Most basic investigations are made with active components. The function, stability, reliability, and the "exotic" parts of a circuit are also dependent on the quality of all components. One of the most underrated components which influences the quality of a circuit is the resistor. Tolerance, the temperature coefficient and TCR, of resistors are properties which add up and, besides this, there are several ageing phenomena which always result in drifts of resistive values, and hence influence stability.

The tolerance of a resistor is always defined as a deviation from stated value of a fresh and unused component and does not say anything about stability during application. When selecting a component, data books, specifications, or standards give an idea what has to be expected when the resistor is in the field for 1000 h or 10 000 h.

These studies can give worst case scenarios where each parameter affecting stability has to be added to the other.

Figure 1 and 2 compare the specifications of typical components of SMT chip resistors in thick film (TCR 100, tol. 1 %) and thin film technology (TCR 25, tol. 0.5 %) for an application at the category temperature of 125 °C according to their data. It becomes very clear that tolerance and TCR are important but not the major influences.

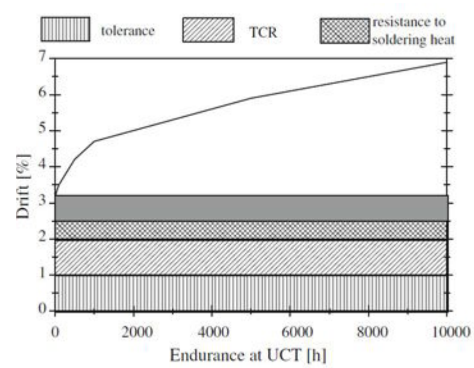

Fig. 1 - Worst case scenario of thick film resistors according to only some of their specifications

For technical questions, contact: melf@vishay.com

Predictable Components: Stability of Thin Film Resistors

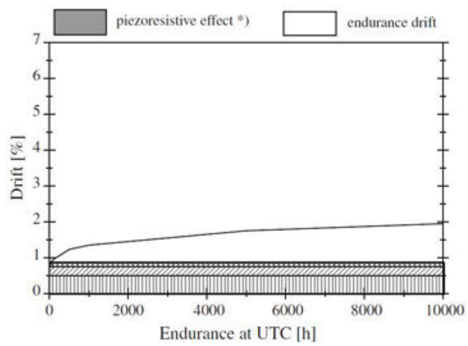

Fig. 2 - Thin film resistors (Prof.) as comparison

The situation is much more complicated. The world has different markets with different standards and specifications for resistors (e.g. Europe: CECC; America + Asia Pacific: EIA; Japan: JIS). Resistors originating from each region are sold world-wide. Can one expect the same properties of resistors from different regions? No, unfortunately not. It is not enough to specify simply a thin film or thick film resistor with tolerance and TCR as seen above. This is one aspect of the whole situation, not more. Figure 3 shows a worst case scenario for some permitted resistor changes due to different specified conditions other than tolerance and TCR, which again could add up.

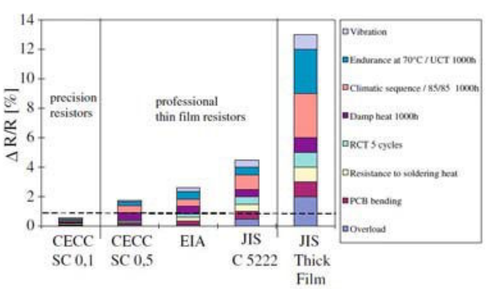

Fig. 3 - Comparison of international specifications of film resistors.

Only CECC knows and specifies stability classes. Different environmental, mechanical, or electrical conditions and permitted changes of resistive value differ from each other depending upon the specification system used.

A thin film resistor is not equal to another and of course can influence a circuit with its own particular worst case condition. In Figure 3 for instance the very important pulse load application and its influences of changes on resistive values are not included.

As it can be seen from this overview there are different influences and ageing mechanisms which can affect the stability and reliability of a resistor.

- Thermal influences from environmental conditions, or ohmic heat which causes chemical changes in resistive films, contacts, coating, and from chemical interactions of those effects in interfaces of these three parameters.
- Chemical reactions due to transport of load
- Chemical reaction due to the presence of water/humidity which can cause electric corrosion to all parts of the component up to the point of destruction of contacts and resistive films.

To conclude these thoughts about specification and reliability:

- For applications where stability in the order of ppm is required, most of the specifications are not sufficient to confidently make the right choice of component
- It is quite obvious that a thin film resistor is able to fulfil stability demands as a cheap mass product with an easy and reliable availability. But even CECC, the only standard which is defining stability classes, is dealing with possible changes of resistive value around 0.5 %.
- The applications in question require more precise and defined declarations

Concering pulse load some contributions have been made (e.g. Möser) and there are data available from independent test institutes. In this Paper we will focus on ageing processes which are based on chemical reactions in thin film resistors during their lifetime.

ROOT CAUSES FOR CHANGES OF RESISTIVE VALUE

Reliability is defined as the influence of laid down conditions on

- Electrical load
- Mechanical stress
- Environmental stress

Changes of resistive value are caused by 4 effects:

- All (!) manufacturing steps of the resistor
- Forming of changed properties from the original state
- Forming of new properties which have not been existent before
- Entry of energy

Predictable Components: Stability of Thin Film Resistors

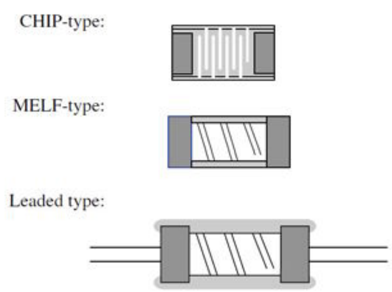

Fig. 4 - Different types of thin film resistors

When analysing the base processes in manufacturing thin film resistors there are six main influences and some in application too.

Main influences on stability of thin film resistors

- Manufacturing process
  - Ceramic: Crystalline transformation at $\upsilon > 1600$ °C
  - Sputtering: High-energy particles are sputtering target material
  - Capping/Manufacturing of contacts
  - Laser trimming: Management of thermal process >> 2000 °C
  - Lacquering
  - Galvanic (Sn)/Welding leads
- Application
  - Pick and place/Mounting
  - Soldering
  - Cleaning PCB/Drying
  - Coating/Moulding
  - Electrical load; temperature; humidity

There are plenty of effective measures to help stabilise a product, e. g.

- Multiple firing of ceramic surface
- Etching of ceramic surface
- Selection of materials
- Heating of ceramic surface before sputtering
- TCR matching
- Ageing of capped or contacted raw resistors respectively
- Ageing after laser trimming
- Ageing after lacquering
- Screenings of ready components
- Pre-ageing of ready resistors
- Burn-in of resistors and/or circuits

Many of these measures are the responsibility of the resistor manufacturer, however, there are some for which the customer is responsible for achieving an optimised stability.

So it is clear that thin film resistors could not all be equivalent because each manufacturer has its own materials and production processes.

STABILITY OF THIN FILM RESISTORS IN ABSOLUTE MEASURE

Especially in analogue applications where high stability over the product lifetime is required, e. g. measurement of temperature in medical application, typical criteria are

> *"SMD components should have a change of resistive value less than 100 ppm or 0.01 % after 5000 h at max. 55 °C and small load"*

Normally, standard test data are available, such as endurance test in upper category temperature for 1000 h. Examples of thin film resistors in chip body sizes 0603 and MELF in 0102 respectively are given in Figure 5. According to CECC the specification for those products are

TYPE	SIZE	STAB. CLASS	ENCURANCE AT UCT
CHIP	0603	0.25	2500 ppm
MELF	0102	0.05	500 ppm

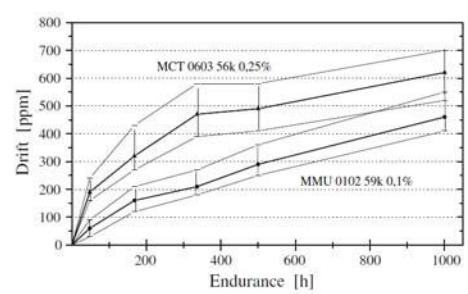

Fig. 5 - Available endurance test data (UCT: 125 °C) in usual graph

When comparing the data with the standard it becomes very obvious that the capability of those components are considerably above the CECC-standard. But how can we predict the drift of those components in case of higher demands and difficult conditions during use? One method which is in use is to make estimations by "rule of thumb", but this is certainly not very satisfactory. It is worthwhile having a closer look into the dependencies and physical rules of these systems.

For technical questions, contact: melf@vishay.com

Predictable Components: Stability of Thin Film Resistors

ARRHENIUS' EQUATION

When looking into the basics of physical chemistry there is a chapter which describes the kinetics of chemical reactions. The fundamental studies, carried out by Svante August Arrhenius, a Shwedish physical chemist (Nobel prize in 1903), have been available since 1889.

The result of his work could be summarised in the three statements:

- Multiple mechanical and thermal stressing lead to an unbalance.
- Every system will attempt to achieve the lowest energy state.
- When a system enters a higher energy state chemical reactions are necessary. In the same manner, also chemical reactions occur in the "opposite" direction, more or less when a lower state of energy appears.

These mechanisms are described by Arrhenius' equation

$$\frac{dM}{dt} = A \cdot e^{-\frac{E_A}{R \cdot T}}$$

where:

$\frac{dM}{dt}$	is the reaction velocity
A	is a material specific constant
E_A	is activation energy
R	is the gas constant, and
T	is temperature Kelvin

By looking up the logarithm of this equation it could be written in a simple form which is similar to the equation of a straight line (y = a · x + b)

$$\ln \cdot \frac{dM}{dt} = -\frac{E_A}{R} \cdot \frac{1}{T} + \ln \cdot A$$

When we transfer the Arrhenius equation in this form we will define it for thin film resistor ageing as

$\ln \frac{dM}{dt}$: al mechanical reactions which will lead to a change of resistive value $\Delta R/R$. They should be expressed as → **ln ($\Delta R/R$)** [ppm]

ln A: A constant number which is related to the particular resistor type (material of layer, process of manufacturing, etc.) and characteristics its overall potential of drift: → **1n ($\Delta R/R$)$_{pot}$** [ppm]

$-\frac{E_A}{R}$: temperature dependence of drift, or how stable is the state of a resistor: → **f(t)R** In [ppm] [K]

These last two numbers can characterise a resistor over the whole temperature area which is in question.

The transferred formula for predicting thin film resistors is

$$\ln\frac{\Delta R}{R}[\text{ppm}] = f(t)R[\text{ppm} \cdot \text{K}] \cdot \frac{1}{T[\text{K}]} + \ln\left(\frac{\Delta R}{R}\right)_{pot}[\text{ppm}]$$

Figure 6 shows the Arrhenius plot for two different layer systems on different SMD constructions

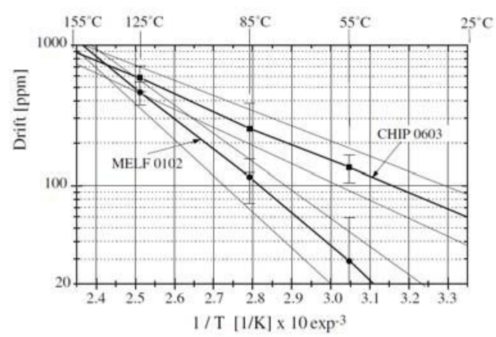

Fig. 6 - Arrhenius plots of thin film SMD resistors after 1000 h endurance tests

When calculating the two characteristic numbers for these systems their differences become very obvious:

SMD TYPE	THIN FILM MATERIAL	f(t)R ln[ppm][K]	ln ($\Delta R/R$)$_{pot}$ [ppm]
Micro MELF 0102	CrNi	-4925	18.4
Chip 0603	CrSi	-2665	13.1

The CrNi material has lower drifts at lower temperatures. But the two characteristics of the film systems show that the CrSi film has a very good potential for precision applications at higher temperatures (lower temperature dependence of drift f (t) R and lower potential drift ln ($\Delta R/R$)$_{pot}$).

Predictable Components: Stability of Thin Film Resistors

PREDICTION OF DRIFT IN TEMPERATURE-TIME-EXPANSE

Arrhenius plots are time-dependent as shown in an example of CrSi thin film resistors in Figure 7. All plots follow the mentioned linear dependencies. Each of them could be described by the characteristic numbers in ($\Delta R/R$)pot and f(t)R.

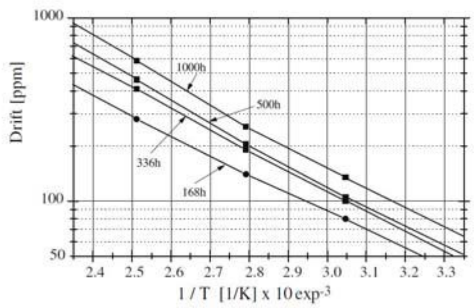

Fig. 7 - Time-dependencies of Arrhenius plots for CHIP 0603 (CrSi thin film)

As shown in Figure 8 and 9 these characteristics show themselves to be linear dependences with respect to time.

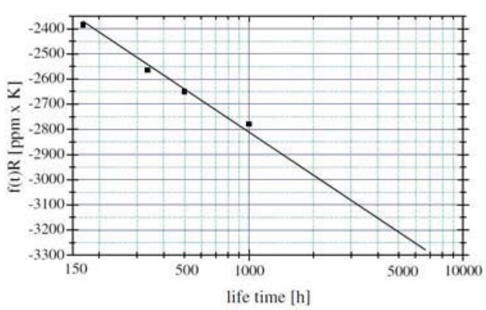

Fig. 8 - Time-dependence of f(t)R for CrSi thin film CHIP resistors size 0603

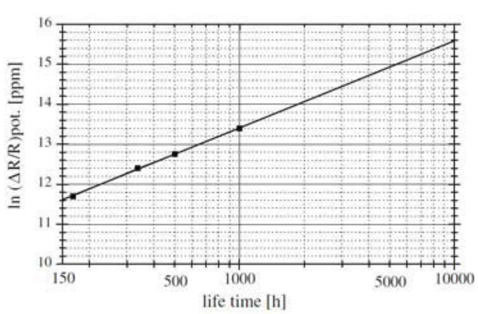

Fig. 9 - time-dependence of ln($\Delta R/R$)$_{pot}$ for CrSi thin film CHIP resistors size 0603

As a consequence, for a particular and defined system the behaviour of a component could be predicted for the whole relevant temperature-time-expanse by one empirical formula.

The formula for the system CrSi thin film resistors (CrSi III) in CHIP size 0603 is

$$\ln\frac{\Delta R}{R}[\text{ppm}] =$$
$$(-1246 - 224 \times \ln t[\text{h}]) \times \frac{1}{T[\text{K}]} + 6.86 + 0.95 \ln t[\text{h}]$$

Examples calculated by the formula:

I: 1000 h , 125 °C → $\Delta R/R$ = 600 ppm (0.06 %);

II: 10 000 h, 155 °C → $\Delta R/R$ = 2300 ppm (0.23 %);

III: 5000 h, 55 °C → $\Delta R/R$ = 202 ppm (0.02 %)

The examples show us very clearly that this MCT 0603 CrSi resistor, 0.25 %, is very stable but actually not suitable for the customer's demand (5000 h, 55 °C, $\Delta R/R$ < 100 ppm). So there is no alternative to choose the CrNi film construction of MICRO-MELF 0102 which will have a $\Delta R/R$ < 100 ppm. This result was achieved in the same procedure as described above.

The extraordinarily stable CrSi thin film system CrSi III will be discussed and compared with other systems in the next chapter.

INFLUENCE OF MATERIAL AND MANUFACTURING PROCESSES

As already mentioned, everything is primarily dependent upon the expertise of the manufacturer in achieving an optimum in terms of reliability and stability of the thin film product.

Figure 10 shows the influence of the different materials (CrSi ratio; amount and type of a 3rd element) and manufacturing processes.

Predictable Components: Stability of Thin Film Resistors

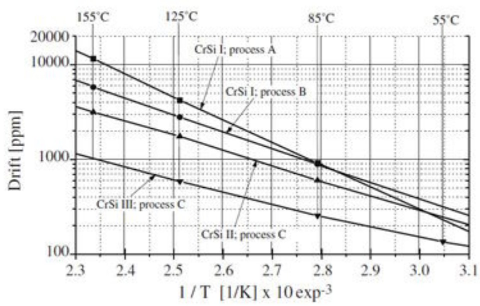

Fig. 10 - Comparison of Arrhenius plots (1000 h) from different CrSi thin film systems and different manufacturing processes

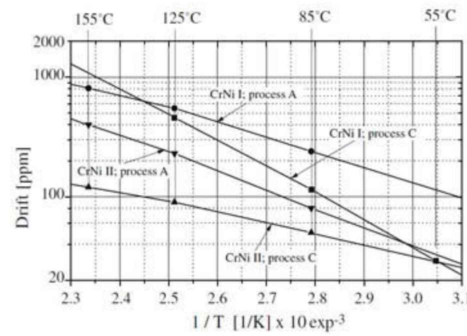

Fig. 11 - Comparison of Arrhenius plots (1000 h) from different CrNi thin film systems and different manufacturing processes.

A second example is shown in Figure 11. As well as CrSi, the CrNi thin film systems show remarkable differences in dependence of materials (CrNi ratio; amount and type of a 3rd element) and processes.

As seen, the stability is not only a question of what basic thin film layer CrNi or CrSi (NiCu, TaN, etc.) is used, but is very strongly dependent on the know-how in material selection and process flow. To illustrate the resistor's differences, table 3 shows a wide spread of different process techniques and thin film materials of CrNi and CrSi in different states of optimisation. They were measured and compared by their Arrhenius parameters $\ln(\Delta R/R)_{pot}$ (drift potential) and f(t)R (temperature dependence of drift). Also the corresponding endurance data are shown in table 3. According to their measured stabilities they are ranked from 1 to 10.

PROZESS TYPE	THIN FILM LAYER CONSTRUCTION	f(t)R ln[ppm] [K]	$\ln(\Delta R/R)_{pot}$ [ppm]	ENDURANCE TEST $\Delta R/R$ AFTER 1000 h [ppm]		RANKING
				55 °C	125 °C	
A	CrSi I	- 5497	22.1	207	3818	10
A	CrNi I	- 4925	18.4	29	399	5
A	CrNi II	- 3385	13.9	35	214	2
B	CrSi I	- 4251	18.6	280	2664	9
B	CrNi I	- 4795	18.0	31	371	4
B	CrNi II	- 3931	14.4	12	89	1 a
C	CrSi II	- 3440	16.0	247	1527	8
C	CrSi III	- 2665	13.1	144	592	7
C	CrNi I	- 2572	12.7	128	502	6
C	CrNi II	- 2497	10.6	20	74	1 b
D	CrNi I	- 3441	14.4	7	323	3

Note

- Comparison of Arrhenius plot characteristics numbers and stability ranking for different thin film materials and manufacturing processes.

Result:

Different manufacturing processes and different modifications of thin film basic materials lead to significant differences in stability results.

The most stable system is the CrNi II modification as well as in process B and C. A remarkable improvement can be seen in the CrSi material. The CrSi III modification in combination with process C is suitable for high precision demands, and its stability is improved by a factor > 6 compared with CrSi I and process A. CrSi III is a benchmark for this type of thin film layer system world-wide.

Predictable Components: Stability of Thin Film Resistors

When showing the data of the characteristic numbers of the Arrhenius plots f(t)*R* dependent on $\ln(\Delta R/R)_{pot}$ - see figure 12 - we make some very surprising and exiting findings.

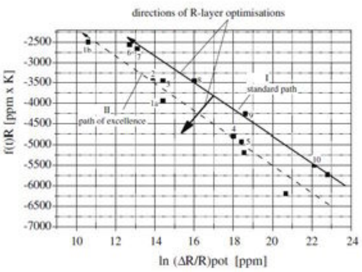

Fig. 12 - Paths of stability - State and rank of all thin film systems and processes are characterised by their position on paths

First of all, the scatter data show a correlation between temperature dependence of drift f(t)R and the drift potential ln(DR/R)pot, as could be expected. But when putting the stability ranking to each result we find two very narrow paths where all the characteristic number combinations tested are lined up according to their ranking.

The paths are named according to the stability states they represent:

- Standard path (precision in top range only)
- Path of excellence (precision and ultra precision)

Improved systems always run along a defined direction of path. Due to the selected thin film material and/or the related manufacturing process the Arrhenius plot characteristic numbers give a certain position for each system on one of the paths.

At the end of the "standard path" the high stabilities of a precision product can already be achieved. The scatter points number 6 and 7 show that stability of CrNi thin film, and a good CrSi thin film resistor is almost equivalent. This is good evidence of the potential still in CrSi thin film for precision application (here the system CrSi III).

LIMITATION TO STABILITY PREDICTION BY ARRHENIUS PLOTS

Prediction of resistor reliability with Arrhenius plots only works when plots are linear and follow the equation. Only those resistors are predictable.

Weaker construction, especially those with high and unstable contact resistances in interface of resistive layer and contact (cap) do not have a linear plot. When contrary and competing chemical reactions in contact/thin film interface, contact, and the thin film are apparent, the Arrhenius plots show non-linear behaviour, especially at the lower temperatures and the early test hours. On the other hand, those circumstances would not allow precision application, so that such resistor qualities are not relevant for an application requiring ppm-level stability.

CONCLUSION

(1) The equation of Arrhenius is transferable to the mechanisms and chemistry of resistor ageing, and is an instrument to describe a thin film resistor's behaviour.

(2) With the two characteristic numbers $\ln(\Delta R/R)_{pot}$ and f(t)R the behaviour of the thin film resistor system can be described.

(3) For a given thin film resistor system the Arrhenius plots can be combined into one formula which makes possible a prediction of the thin film resistor's reliability and ageing over the whole relevant temperature-time-expanse.

(4) At stability requirements in the sub-thousendth range it becomes very clear that a manufacturer's expertise in process and selection of thin film materials is crucial, and the major factor for the resistor's reliability properties.

(5) Stability properties of CrNi and CrSi thin film resistors may differ by a factor of 2 to 5 due to choice of materials and processes.

(6) Characteristic numbers of Arrhenius plots characterise the state of stability of a thin film resistor system due to their positioning on the "paths of stability". They are valueable tools as quality indicators for development and optimisation of thin film properties and their evalution.

REFERANCES

Kühl, R. W. (1998). "Piezoresistive Effects on Chip Resistor Application in SMT", proceedings CARTS-Europe 1998, pages 83 to 91.

Möser, R. (1995), "Chip Resistors: Pulse Load Capability and Current Noise", Proceedings CARTS-Europe 1995, pages 139ff.

Ulich-Jost. (1970), "IV Chemische Kinetik" (German). Kurzes Lehrbuch der physikalischen Chemie, Dr. Dietrich Steinkopf Verlag, Darmstadt, pages 241 to 261.

Ackmann, W. (1976), "Prüfung der Zuverlässigkeit" (German), Zuverlässigkeit elektronischer Bauelemente, Hüthig Verlag, Heidelberg, pages 38 to 45