Improved stability of thin-film resistors

Circuit designers often use the time-dependent form of the Arrhenius equation to predict drift in thin-film resistors. Relying on this equation, designers can model resistive-value changes due to aging for any relevant condition in the temperature -time expanse during the resistor's application. In recent years, this model has been utilized in the development of new thin-film resistive layers.

Reiner W. Kuehl, Vishay Draloric/Beyschlag Division -- EDN, June 15, 2011

Earlier, deeper investigations into the drift behavior of thin-film resistors have shown that the usual methods for predicting drift are incapable of describing the present remarkable differences within a certain R-layer alloy system (for example, CrNi) or those between different alloy systems (for example, CrNi versus CrSi or TaN). In order to come to a more precise model, we have to ignore all available and published models and start again with a different approach based on the general Arrhenius law (**references 1** and **2**).

The transferred equation for predicting drift in thin-film resistors is

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

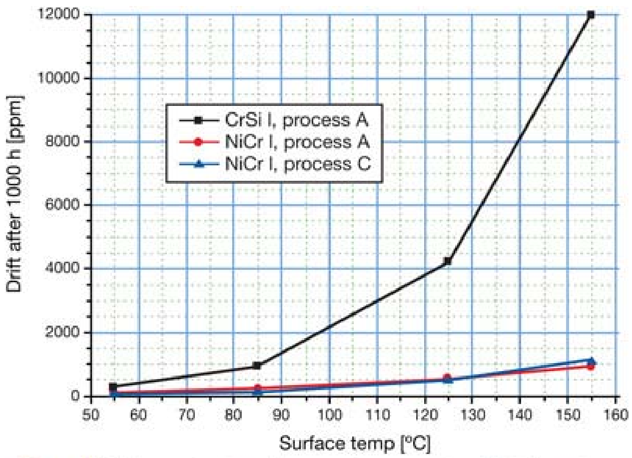

Figure 1 Endurance-test results versus temperature (1000 hours)

Figure 1 shows that the drift in an endurance test is dependent on the temperature of the two different thin-film alloys and two different manufacturing processes. When transferred into the Arrhenius form, we see a good linear fit and accordance to the law (**Figure 2**). A description of the resistors by the numbers *ln* $(\Delta R/R)_{pot}$ and *f(t)R* can easily be derived from **Equation 1** above.

The above **equations** contain the empirical time-dependent adaptation factors of these system constants to the measured irreversible drifts after certain exposure times. By accepting and integrating this obviously deviating, but well reproducible, phenomenon into the Arrhenius equation, the aging behavior of thin-film resistors can be described precisely.

By defining the necessary time-dependence terms shown here,

$$f(t)R\,(t) = B*\ln(t[h]) + C$$
$$\ln(\Delta R/R)_{pot}(t) = D*\ln(t[h]) + F$$

we achieve the newly developed final formula for predicting thin-film-resistor stability:

$$\ln \Delta R/R\,[ppm] = (B*\ln(t[h]) + C*\frac{1}{T[K]} + D*\ln(t[h]) + F$$

This model and formula enable us to predict the thermal aging behavior for a particular and defined thin-film system, and for the whole relevant temperature-time expanse over which the component is to be used.

Enhancement of resistive film

The majority of general-purpose thin-film resistors are nichrome devices using nickel-chromium technology. Our examples in **Figure 2** have shown that the stability of a thin-film system is strongly dependent both on the material (alloy) and on the process applied.

Improvements in stability can be shown graphically using, for example, the upper category temperature (UTC) +155ºC for 1,000-hours data for *f(t)R* and $\ln(\Delta R/R)_{pot}$, defined above.

Figure 3 shows the optimization steps for three different thin-film alloys achieved over the past few years in terms of their characteristics *f(t)R* and $\ln(\Delta R/R)_{pot}$. The small arrows indicate small improvement steps on the same path, while the big arrows indicate the transfer to the next level (parallel paths to the left).

This research has identified enhancements to the basic composition and the related processes, resulting in greater stability with respect to temperature and humidity. This has been achieved by the addition of a third constituent to the nickel-chrome matrix, and the optimization of the matrix and sheet resistance parameters, process conditions, etc.

This new thin-film development allows production of thin-film resistors capable of withstanding surface temperatures up to +175°C, and which are stable up to and beyond the maximum allowable operating temperature for enhanced Pb (lead)-free solder joints rated to +150°C (for example, Innolot).

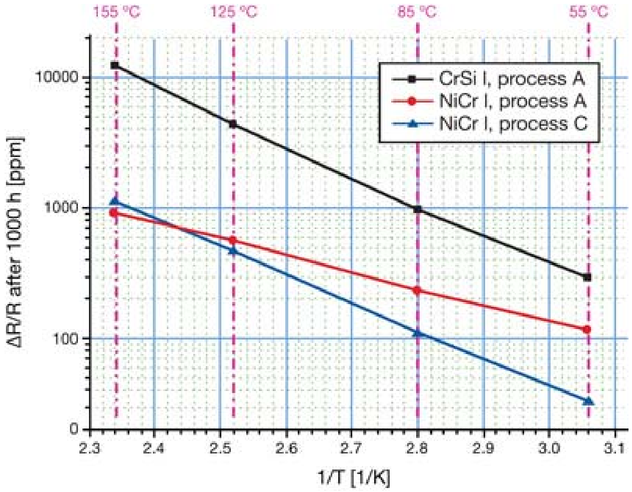

Figure 2 Results of Figure 1 transferred into Arrhenius form

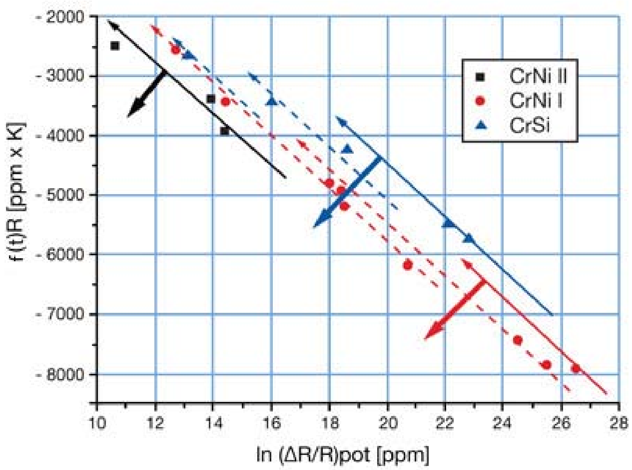

Figure 3 Optimization of three different thin-film alloy systems

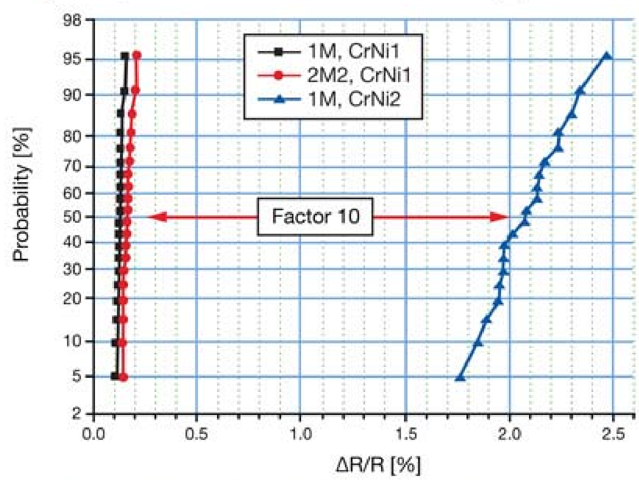

Figure 4 CrNi 1 and 2 after 1,000 hours at UCT +175°C

Figure 4 compares the stability of a standard NiCr2 thin-film alloy with that of a next-generation device incorporating the enhanced CrNi1 film composition. This new composition has also been engineered to display higher activation energy, leading to improved stability (by a factor of 10, especially at high ohms) and reliability.

High-temperature lacquering system

A high-temperature lacquering system has also been developed that allows for sustained use at up to +175°C, as well as providing sealing and humidity protection for the lifetime of the component. This specially developed, highly filled epoxy-acrylate system is approved and released based on sequential testing of 1,000-hours storage at the UTC of +175°C, 500-cycle rapid changes of temperature from -55 to +155°C, and testing of humidity ratings through HAST 130 (highly accelerated temperature and humidity stress test). **Figure 5** shows the achievements of this accelerated test, simulating the worst-case temperature and humidity stress during use in the field.

The degradation mechanisms of the thermal aging of lacquer and the resistive layer are different. Both have to be thoroughly taken into account to ensure their main properties, as described later in this article: sealing against humidity (lacquer) and R-drifts (R -layer).

High-temperature thin-film resistors

The recent advances in film technologies and packaging materials (marked as "HT-type") have enabled new generations of thin-film resistors to achieve stability (stab class 0.25 at +175°C UCT), reliability, and high load in relation to case size that have not previously been encountered in mass-market resistors.

Figure 6 compares the performance of HT (high-temperature) MMU0102 thin-film resistors (equivalent to the 0805 case size) against the conventional Micro-MELF thin-film equivalent, as well as corresponding commodity resistors in 0805 and 0603 SMD packages. The diagram illustrates significantly higher load-carrying capability of the HT-enhanced resistor, over and above the fundamental power-density advantage that thin-film technology delivers compared with thick-film alternatives. This example illustrates the general advantages of using the new high-temperature resistors, which remain true for Mini-MELF-HT and, to a certain extent, for CHIP-HT sizes, as well.

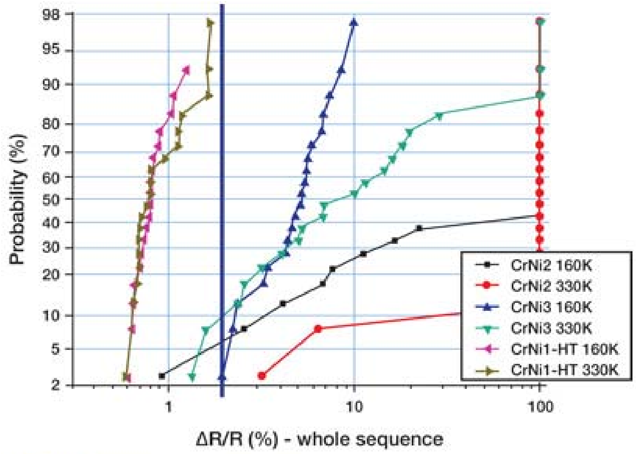

Figure 5 Sealing properties versus design

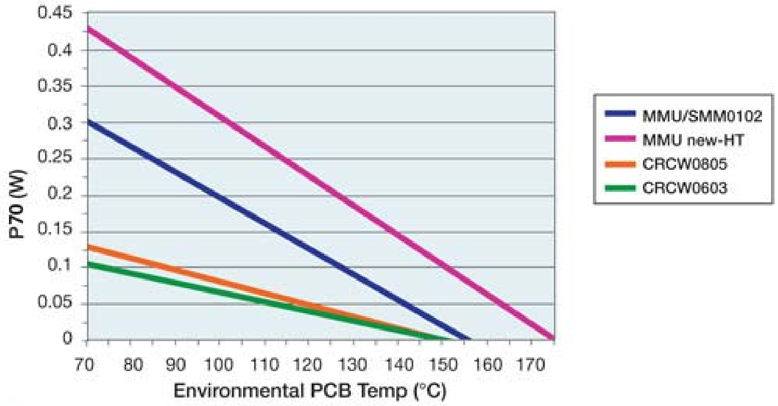

Figure 6 Comparison of load capabilities at high temperatures

In CrSi thin-film layers, similar achievements can be made, as already indicated in **Figure 3**. A real example of an R-layer improvement is shown in **Figure 7**.

Alloy and process optimization have led to a factor-of-10 improvement in drift performance at high temperatures with the new CrSi 1. Furthermore, this system is remarkably desensitized to surface-temperature increases between +125°C and +175°C and drift or aging behavior, respectively.

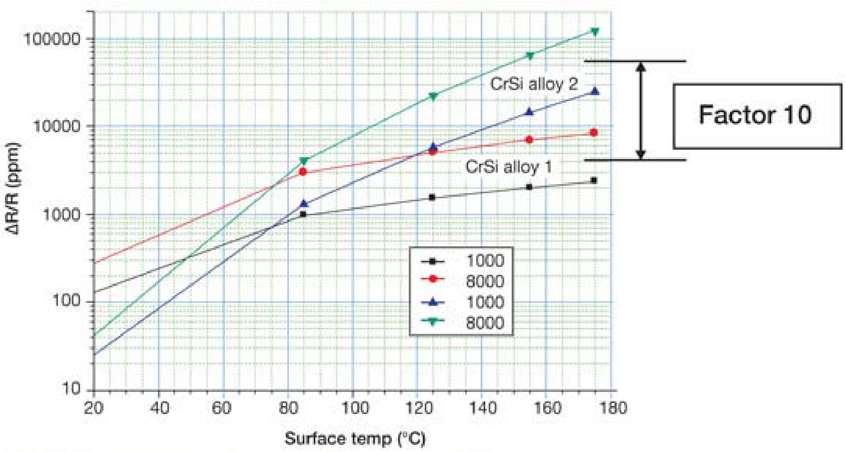

Figure 7 Comparison: CrSi>332 K, alloy 1 and 2; valid for 98%

Prediction: mission profiles

The automotive industry requires aging and reliability predictions for the entire lifetime of electronic equipment in cars. Similar demands are coming from the aerospace industry, as well. The model introduced here can help to predict the stability of thin-film resistors in these applications. To meet these extended requirements, mission profiles are defined for certain automotive applications, such as 20 hours at +205°C; 250 hours at +175°C; and 8,000 hours at +145°C. Simply by transferring these formulas into an Excel spreadsheet, each mission profile can be calculated for all relevant temperature-time expanses.

Figure 8 shows the Excel worksheets and an example of an HT-type Mini-MELF device for a four-level mission -profile calculation: 18,500 hours at +85°C; 5,000 hours at +130°C; 500 hours at +150°C; and a differentiation at the high-temperature range at 400 hours at +175°C versus 250 hours at +200°C. Detailed guidelines for the achievement of full temperature-time expanse predictions are described in **Reference 2**.

We have to obey all relevant thermal degradation and aging parameters of the resistor and R-layer (drift), as well as lacquer (sealing, protection against humidity diffusion). The resistance change of a known system is strongly dependent on the applied temperature and time. This integrated temperature by time is used to define

Entrance of Missionprofile MMA-HT ≤ 68 K, max 200 °C		
Temperature in °C:	Time in h:	
85	18500	dR/R = 31 ppm
130	5000	dR/R = 227 ppm
150	500	dR/R = 65 ppm
175	400	dR/R = 173 ppm
(a)	Total life time drift prediction →	dR/R = 496 ppm ... or 0.05 %

Entrance of Missionprofile MMA-HT ≤ 68 K, max 200 °C		
Temperature in °C:	Time in h:	
85	18500	dR/R = 31 ppm
130	5000	dR/R = 227 ppm
150	500	dR/R = 65 ppm
200	250	dR/R = 271 ppm
(b)	Total life time drift prediction →	dR/R = 595 ppm ... or 0.06 %

Figure 8 Mission profile calculation 1 (a) and calculation 2 (b)

the limit of the allowed degradation of the lacquer, as well (equivalent to +175°C at 1000 hours).

The above example of a stable HT resistive layer predicts a very low drift of resistive value of 0.05% maximum after application of the mission profile; the associated lacquer degradation remains within limits (green background of drift result).

Calculation 2 still shows a very low drift of resistive value, but in this case the lacquer degradation limit is exceeded (red background of drift result; not a recommended application).

Conclusion

The time-dependent Arrhenius equation is a suitable tool for describing a resistor's drift behavior over relevant temperature-time expanses. Characteristics discovered by this means can be used for development, design, drift, or drift-factor prediction, and to calculate mission profiles for components.

The latest advances in Pb-free solder alloys provide additional assurances for designers of assemblies such as automotive or industrial systems, where target environments impose sustained high junction temperatures, wide thermal cycling, and high demands for reliability. Using these solders (such as Innolot), operating junction temperatures up to +150°C can be sustained without compromising solder-joint reliability. However, for devices such as conventional thin-film resistors, these temperatures are close to the maximum recommended body temperature. With only a relatively small load current, Joule heating can cause the device to exceed this maximum, thereby compromising stability and reliability.

A new thin-film-resistor technology combines high-temperature materials to safeguard performance in high-temperature applications with higher specified levels of stability and in smaller sizes—at constant or higher specified loads—than possible with existing Pb-free technology. Similar high-temperature resistor components have been developed in the Mini-MELF (0.5W; equivalent to the 1206 size) and rectangular chip size (automotive series, rated to +175°C).

Prediction models based on a time-dependent form of the Arrhenius equation can ensure safe and reliable operation in high-temperature applications while providing an indication of the stability benefits provided by these new resistor types in normal-temperature applications, as well.

References

1. R.W. Kuehl, Predictable Components - Stability of Thin Film Resistors, Proceedings CARTS-USA 2000 Huntington Beach (2000) 155 -161.
2. R.W. Kuehl, Stability of Thin Film Resistors – Prediction and Differences Based on Time-Dependent Arrhenius Law, Microelectronics Reliability 49 (2009) 51–58.

Author's information

Reiner W. Kuehl has been with Vishay since 2002 and is currently senior manager, "Customer Complaints & Quality Projects," for the company's Draloric/Beyschlag resistor division. He studied physical technology at the University of Applied Science in Lübeck, Germany, graduating with a Dipl. Ing. degree, and has more than 25 years of active experience in the industrial research and development of passive electronic components.