# Zero TCR Foil Resistor
# Ten Fold Improvement in Temperature Coefficient

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## ABSTRACT

Foil resistors have been the leading in precision and stability, since introduced in 1962.
One of the important parameters influencing stability, is the Temperature Coefficient of Resistance (**TCR**). Although the TCR of foil resistors is considered extremely low, this characteristic has been further refined over the years.

The resistance change versus temperature is a non-linear function, and it is extremely low to begin with. Therefore the key to improve further the temperature dependency was to find a way to linearize this function, or to reduce the non linear component first, and then reduce the slope (linear component) of resistance versus temperature (TCR) to zero or as close to zero as possible.
This paper describes such a resistor. Its nominal TCR was reduced to -0.2 ppm/°C from –55°C to +25°C and +0.2 ppm/°C from +25°C to +125°C, this is a 5 fold TCR improvement over the best previous available foil resistor and a 10 fold improvement over standard foil resistors.

## HISTORY

In 1962 Vishay Intertechnology was assigned a series of patents[1] for a new technology of manufacturing state-of-the-art precision resistors exhibiting a very low temperature coefficient of resistance (TCR)[2].

[1] Filed by F. Zandman et al.
[2] TCR at a given temperature T is defined as $TCR = \Delta R/[R(\Delta T)]$, but usually refers to a temperature span from a reference $T_0$, and then $TCR = (R_T - R_0)/[R_0 (T - T_0)]$ and is represented by the slope of a chord on the $\Delta R/R = f(T)$ (Resistance – Temperature Characteristic) curve.

## CONSTRUCTION OF RESISTORS

These resistors are made as follows:
A foil of Ni-Cr, or similar alloy, about 3 µm thick, is heat treated to adjust its TCR and bonded to a solid ceramic substrate, of thickness about 0.5 mm

A photosensitive resin is then deposited on the foil using microelectronic processes. The photosensitive resin is exposed (photolithography) through a photographic mask representing the design of resistance circuit, which resembles a series of looping filaments. The resin on non-exposed areas is washed off, leaving the resin on exposed areas in the form of a meander pattern on top of the foil. The foil areas not protected by the resin are then etched, reproducing the design of the mask. This step creates a multitude of resistive filaments interconnected in series or parallel such that the resistance of the circuit reaches the desired value and can be later adjusted. The resulting wafer, containing many resistor elements, is next singulated into resistor chips. The chips are adjusted to the desired tolerance by cutting designed-in shunts.
Packaging the chip to form a discrete resistor in a way to avoid outside mechanical stresses completes the manufacturing process.

## PRINCIPLE OF OPERATION

Behavior can be explained as follows:
The electric resistance of the foil in its free state (before bonding to a substrate) increases with temperature. Since the foil is cemented to the much thicker ceramic substrate and since the coefficient of thermal expansion (TCE) of ceramic is smaller than the TCE of the foil, as the temperature rises, the foil undergoes compressive stress and therefore the resistance decreases.
If both phenomena are equal and of opposite sign the resulting change is zero. This is the essence of the low TCR of foil resistors.

The net temperature sensitivity of the integral resistor package could be reduced to zero if both effects were linear, equal in magnitude, and of opposite sign.

Actually the Ni-Cr alloys known under their trademarks like Evanohm, Karma or Moleculoy claim a TCR of 65 ppm/°C from -55ºC to 25ºC (cold range) and from 25ºC to 125°C (hot range). They are the most linear of the alloys used for production of precision resistors, but still their TCR contain a small nonlinear component. The alloy is treated so that after matching the foil with the substrate the resulting resistance change will vary a minimum amount around a reference temperature, usually 25°C. With proper centering of the ΔR/R = f(T) curve's extreme point at x=25°C, a low TCR (as depicted by this curve's chord slopes) is obtained, with cold slope and hot slope of similar magnitude but opposite sign (fig. 1 & 2).

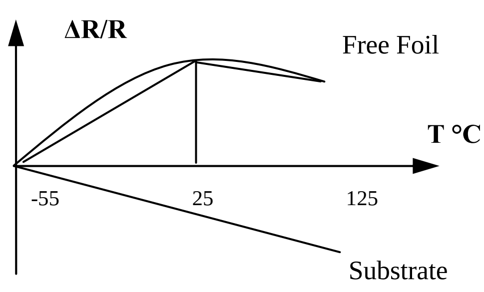


**Fig. 1. Free Foil and Substrate.**

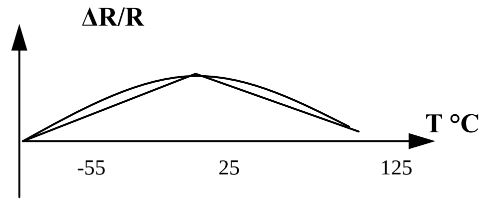


**Fig. 2. After bonding.**

## TCR CONTROL AND ALLOWABLE STRESSES

The existence of internal stresses in the resistor leads to the consideration of stability and TCR control [1,2]. In order for these properties to remain completely reversible and repeatable, stresses in the foil and the substrate must be predictable and should not approach their respective yield points. The materials used in production of foil resistors have the following characteristics:

Moduli of elasticity:
Foil $E_f$ = 22 000 kg/mm$^2$
Substrate $E_s$ = 30 000 kg/mm$^2$
Yield point of foil = 85kg/mm$^2$
Poisson ratio for both materials:
$\mu$ = 0.3 (approx.)
Coefficients of thermal expansion:
Foil $\alpha_f$ =13 ppm/°C
(ppm = parts per million)
Substrate $\alpha_s$ =6 ppm/°C

Both materials behave like Hookian elastic bodies.

Because the substrate is more than 100 times thicker than the foil and since their modulus of elasticity are of the same order of magnitude, thermal stresses in the substrate due to the difference in coefficient of thermal expansion of both materials would be entirely negligible.

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[1,2] Paper by F. Zandman and S. J. Stein "A new precision film resistor exhibiting bulk properties", IEEE publications, 1962
Some of the coefficients are different in this paper as materials presently used are different.

The thermally induced strain in the foil, for a change in temperature $\Delta T$, is

$$(\Delta l/l)_T = \varepsilon_T = (\alpha_f - \alpha_s) \cdot \Delta T$$

For $\Delta T = 1°C$, $\varepsilon_T = (13 - 6) \cdot 10^{-6} \cdot 1 = 7$ ppm

For an operating range between –55°C to 125°C, $\Delta T = 180°C$, the thermal strain will be

$$\varepsilon_T = 180 \cdot 7 = 1260 \text{ ppm.}$$

The strain is transmitted by the glue to the foil equally in direction of the filaments of the resistive circuit and in the lateral direction.

The corresponding thermal stress $\sigma_f$ induced in foil's filaments is:

$\sigma_f = E_f \cdot (\alpha_s - \alpha_f) \cdot \Delta T/(1-\mu) = E_f \cdot \varepsilon_T/(1-\mu) = 39.6 \text{ kg/mm}^2$, providing a safety factor of over 2. Thus, such thermally induced stresses are safely below the yield point and do not cause plastic flow in the foil. Use of other foil materials, of lower Modulus of elasticity and Yield point or leading to a larger difference between the coefficients of thermal expansion of foil and substrate, may lead to non-reversible changes of resistance due to thermal stress.

The thermal strain causes a linear change of the resistance;

$$(\Delta R/R)_{ts} = k \cdot \varepsilon_T = c \cdot \Delta T$$

The coefficient k is called gage factor[3].

The constant c represents the thermal strain related component of the TCR.

The non-linear change of resistance of the *free material* (non-strained foil) can be expressed by a quadratic equation:

$$(\Delta R/R)_{fm} = a \cdot \Delta T + b \cdot \Delta T^2$$

The Resistance Temperature Characteristic of a foil resistor can therefore be represented by a curve combining the above two effects:

$$\Delta R/R = (a + c) \cdot \Delta T + b \cdot \Delta T^2$$

To minimize the temperature induced changes of resistance, the linear coefficients a and c should cancel each other and the non-linear coefficient b should be reduced.

The resulting TCR, or $(\Delta R/R)/\Delta T$, is usually expressed by the two chord slopes of the curve, representing the cold (-55°C to 25°C) and the hot (25°C to 125°C) temperature ranges.

The popular Vishay Style S102C resistor has nominal cold and hot chord slopes of : +2.2 ppm/°C and -1.8 ppm/°C respectively - see fig. 3.

**S102C Typical TCR**

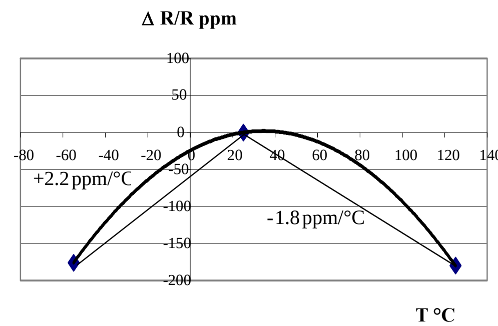


**Fig. 3 C-alloy Resistance - Temperature Characteristic**

An improved performance was achieved in the S102K style by use of foil of a different alloy. Nominal chord slopes of –1 ppm/°C and +1 ppm/°C respectively were obtained.

Compared to the TCR of Style S102C resistors, the slopes were reduced by a actor of two and had opposite signs – see figure 4.

**S102K Typical TCR**

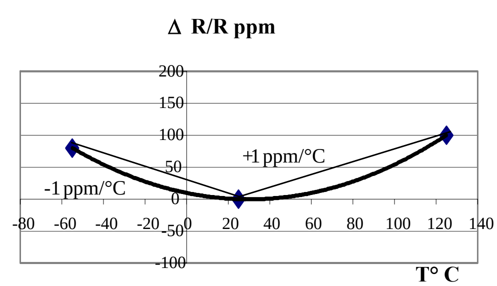


**Fig. 4 K-alloy Resistance - Temperature Characteristic**

[3] The value of gage factor k depends on the relation between strain and volume and on the influence of stress on material's electrical resistivity.

It characterizes different materials and is established empirically. For the foil's Ni-Cr alloy k equals approximately 2, depending on geometry of resistive lines and type of Ni-Cr alloy used.

The combination, in series or in parallel, of these two styles is a rather costly way to reduce the TCR.

Resistance Temperature Characteristic of S102C + S102K is shown in fig. 5:

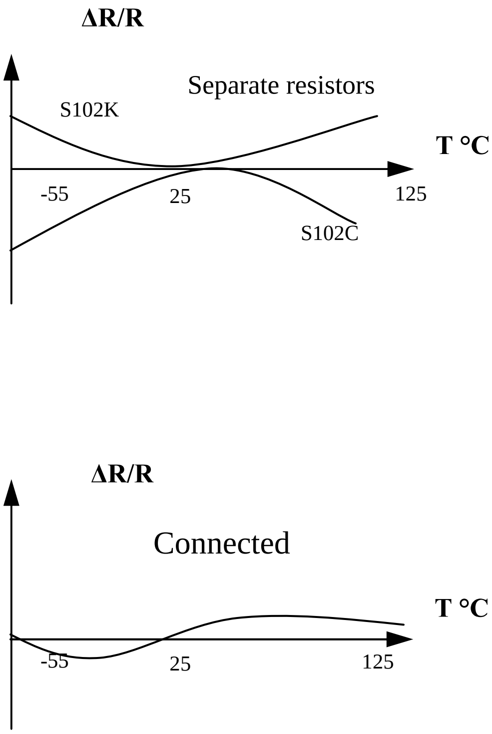


**Fig. 5. Connection of S102C and S102K resistors**

Similar results were obtained by modifying the construction of the substrate of the S102C style resistors: The substrate's TCE was made non-linear in a way to compensate the non-linearity of the TCR of the foil (fig. 6).

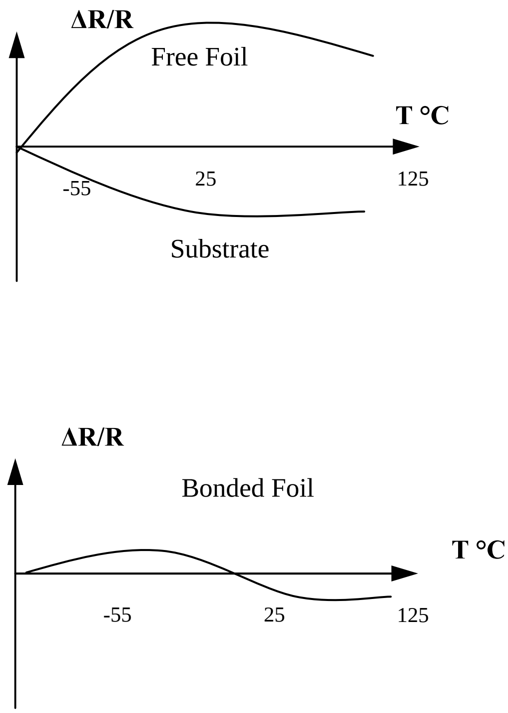


**Fig. 6. S102C with Modified Substrate**

The latest achievement (February 2000) came with the development by R. Goldstein of the new Vishay Z alloy that inherently exhibits a very small non-linearity of the Resistance Temperature Characteristic. As shown on illustration below, the new resistor has TCR slopes of –0.2 ppm/°C (cold) and +0.2ppm/°C (hot) for the military temperature range of –55°C to 125°C (fig. 7).

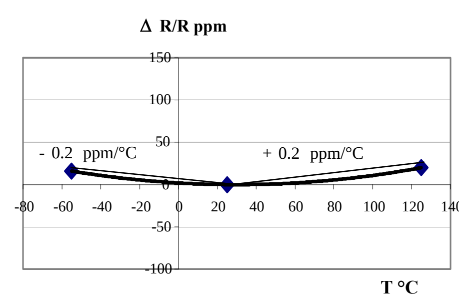


**Fig. 7. Z- Alloy Resistance -Temperature Characteristic**

Fig. 8 shows a TCR chord slope comparison between the three types of foil resistors produced with C alloy, K alloy and Z alloy.

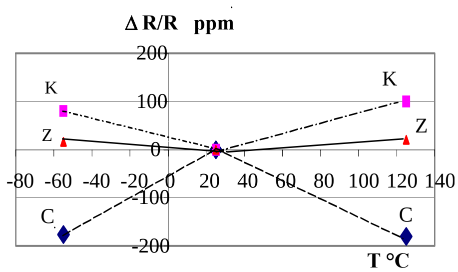


**Fig. 8. Comparison of nominal TCR slopes of alloys C, K and Z**

## MEASUREMENTS

Samples of different molded and hermetic packaging configurations were given to some customers for evaluation. Below are test results supplied by Metron Design of hermetic oil filled samples measured in a temperature range 20-40°C.

| # | TCR ppm/°C | Estimated uncertainty ppm/°C |
|---|---|---|
| 1 | -0.25 | 0.03 |
| 2 | -0.03 | |
| 3 | 0 | |
| 4 | +0.2 | |

## SUMMARY

The reduction of the non linear component of the resistance/temperature function of the Ni-Cr alloy is at the core of the new foil resistor exhibiting the lowest TCR achievable today.

The progress can be expressed by the slopes of the cold and hot temperature ranges of the respective curves:

**Nominal Slopes, in ppm/°C**
(-55°C to +25°C and 25°C to 125°C)

| Vishay Style | Year | Cold | Hot |
|---|---|---|---|
| S102C | 1962 | +2.2 | -1.8 |
| S102K | 1980 | -1.0 | +1.0 |
| Z201 | 2000 | -0.2 | +0.2 |

The nominal slopes were reduced from 2.2/1.8 trough 1 to the lowest value 0.2, or in other words a 10 fold improvement.

## REFERENCE


Resistor Theory and Technology
Scitech Publishing. Inc. Mendham, NJ, US