Strain Sensitivity in Thick-Film Resistors

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Abstract—**Piezoresistive properties of Dupont 1400 series thick-film resistors have been investigated by measuring longitudinal and transverse gauge factors as a function of applied strain between 0 and ± 1000 microstrain in the temperature range from −70 to + 140°C. The relative change in resistance of thick-film resistors is linear, reproducible, and hysteresis free for the full range of applied strain. They appear more sensitive than metal resistors and have a low temperature coefficient of resistance (TCR) and gauge factor.**

INTRODUCTION

THE INTEREST in piezoresistive properties of resistors is twofold. In basic research they provide information on the transport mechanism and sometimes on the electronic structure of solid-state materials [1], while in applied research such information will largely determine the suitability of specific materials for strain-sensing applications [2]-[4].

An ideal strain gauge should have a high piezoresistivity effect together with a negligible thermoresistive effect; more precisely, a high gauge factor, GF $= \Delta R/R\epsilon$, is required ($\Delta R/R$ is the relative change of the resistance for an applied strain ϵ) associated with a low temperature coefficient of resistance, TCR $= \Delta R/R\ \Delta T$ and TCGF $= \Delta\mathrm{GF}/\mathrm{GF}\ \Delta T$ where ΔT is the temperature range where ΔR and ΔGF are considered. Moreover, a stable behavior is required, i.e., the resistance and gauge factor should remain stable with time and under the operating conditions.

Today commercially available strain gauges use semiconductor or metal-film resistors. The former are characterized by high GF, but also high TCR and TCGF, while the latter have low GF and moderate TCR and TCGF.

Strain gauge resistors of the discontinuous metal film and cermet type have found very limited application up to now because, in spite of their high strain sensitivity and moderate TCR and TCGF, they have not shown adequate reproducibility and stability. Some cermet resistors with suitable stability were obtained by means of post-deposition treatments but these treatments lowered the gauge factor values [5].

Thick-film resistors, because of their structure, can be considered as cermet resistors with high stability [6]. This latter property is probably a consequence of the nature of conductive grains (metal oxide or metal oxide compounds) and of the firing temperature. Moreover, in both thick-film and evaporated or sputtered cermet resistors, the conduction mechanism is mainly due to electron tunneling between conductive grains through a dielectric matrix [7]-[10]. This tunneling mechanism should be responsible for high gauge factors and low TCR and TCGF.

Starting from these considerations, we have investigated the piezoresistive properties of thick-film resistors. The results presented in this paper refer to a widely used thick-film resistor series, namely, Dupont 1400.

SAMPLES AND EXPERIMENTAL MEASUREMENTS

A ruthenate based thick-film system was studied (Dupont 1400 series). Resistors were prepared on alumina substrates according to the usual procedures of screen printing, drying, and firing processes well-known in microelectronic hybrid circuits [11].

Silver-free terminations were provided for all resistors in order to avoid metal migration effects [12]; we used Dupont 9596 platinum-gold based terminations. Gauge factors were measured by bending a cantilever beam clamped at one end and measuring the deflection by a micrometer. On the same cantilever (5 × 1 × 0.06 cm) and at the same distance from the clamped edge, two resistors 1 × 1 mm were located so that both longitudinal and transverse gauge factors could be measured. The strain applied to the resistors was calculated by well-known formulas [4]. The validity of the procedure was checked by means of calibrated silicon strain gauges glued on the alumina substrate very close to the thick-film resistors. In this way we evaluated the total error in the computed strain values to be less than 3 percent.

In addition to gauge factors, resistance, TCR, and TCGF were measured with a digital multimeter with an accuracy of one over six digits. Temperature in TCR and TCGF measurements was stable within ±0.5°C in the range of −70 to +140°C.

For TCGF measurements the resistors were prepared on long and narrow (5 × 1 cm) alumina substrates to enable bending beam experiments to be carried out. The beam was supported at the edges and loaded with a constant weight at the center on the opposite side of the beam where measured resistors were located. In this way a constant strain of 500 microstrain was applied throughout the whole temperature range.

EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 1 shows the relative change of resistance, $\Delta R/R$, in $10^5\ \Omega/\square$ resistors at room temperature for compressive and tensile strain (from 0 to 1000 microstrain) applied normal and parallel to the current direction. It is evident that 1) the resistance decreases in compression and increases in tension in both cases (longitudinal and transverse strain); 2) the relative change in resistance is linear in the whole range of the applied strain, and the lines through the data points cross the zero point contrary to what was observed in preliminary experiments by

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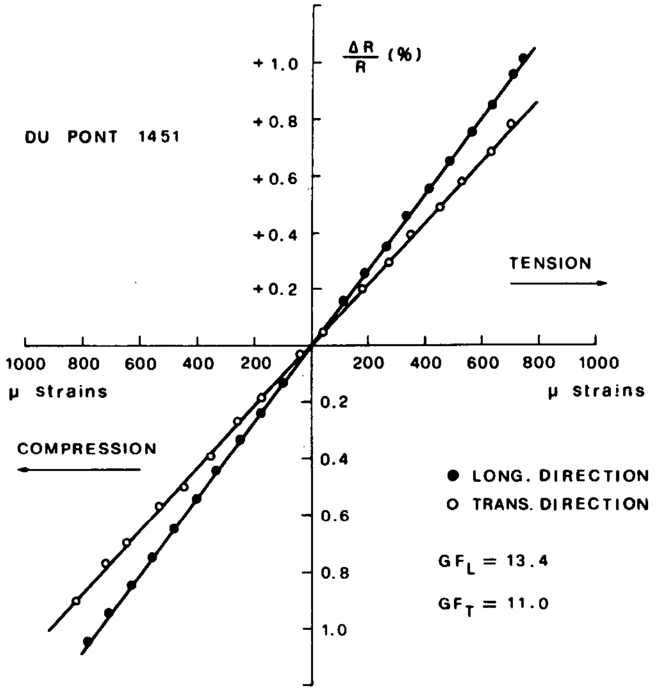

Fig. 1. Relative change of resistance for compressive and tensile strain applied normal and parallel to current direction in Dupont 1451 resistors (100 kΩ/□) at room temperature.

Holmes [13] on different Birox Dupont resistors; 3) for an applied strain of 1000 microstrain, a $\Delta R/R$ of the order of ±1 percent is observed. Data shown in Fig. 1 are reproducible and hysteresis free, clearly showing their dependence on elastic distortion of the resistor structure rather than on any permanent damage. At room temperature it was observed that the relative change and unstressed resistance were fully repeatable even after thousands of bending cycles. Similar relative changes of resistance as a function of the applied strain are observed for all sheet resistivity of Dupont 1400 series. The slope of the straight lines shown in Fig. 1 gives $GF_L = 13.4$ and $GF_T = 11$, for the longitudinal and transverse gauge factor, respectively.

It has been shown [4] that, for isotropic material, a well-defined difference exists between measured longitudinal and transverse gauge factors. This difference is determined by the Poisson ratio of the substrate ν and is independent of the physical properties of the resistor material:

$$GF_L - GF_T = 2(1 + \nu). \tag{1}$$

The results of Fig. 1 agree well with (1) since, in our case, $GF_L - GF_T = 2.4$ and $2\,(1 + \nu) = 2.44$ suggesting that our thick-film resistors behave as an isotropic material. Moreover, the high values of the measured gauge factors point to a dominant role of the transport mechanism with respect to geometrical change induced by strain in the strain sensitivity of thick films. In fact, geometrical changes give gauge factors less than about 2.5.

Fig. 2 shows the longitudinal and transverse gauge factor values as a function of sheet resistivity of the screen-printed and fired resistors obtained by Dupont 1400 inks (1, 10, and 100 kΩ/□). Similar to what was observed in evaporated or sputtered cermet resistors, the gauge factors decrease on decreasing the film resistivity [5]. Nevertheless, in our case this decrease is moderate, so that we have an interesting strain sensitivity over a wide resistivity range.

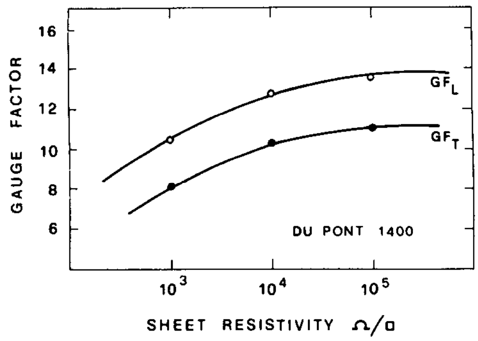

Fig. 2. Longitudinal and transverse gauge factors as function of sheet resistivity of screen-printed and fired resistors obtained by Dupont 1400 series inks.

The temperature dependence of resistance in a strained and unstrained resistor is shown in Fig. 3. It is evident from this figure that the applied strain does not change the thermal behavior of the resistors. In fact, both the shape of the resistance versus temperature curve and the temperature value at which TCR vanishes seem to remain unchanged under strain application. TCR values lower than ± 100 ppm/°C are obtained in the temperature range from −80 to +120°C.

The temperature dependence of the longitudinal and transverse response of resistors under 500 microstrains is reported in Fig. 4. In the whole temperature range considered TCGF is lower than ±200 ppm/°C.

CONCLUSION

In this work the results of an analysis of the strain sensitivity of a widely used thick-film resistor series (Dupont 1400) have been reported. The work extends a previous investigation by Holmes [13] who pointed out possible large changes of thick-film resistor values under substrate flexure. Data on longitudinal and transverse gauge factors and temperature dependence of longitudinal gauge factors are included as well as an indication of good stability and perfect linearity in tension and compression from 0 to 1000 microstrains. The obtained results point out that thick-film resistors behave under strain application as isotropic material and that the transport mechanism plays an important role in the piezoresistivity effect, with respect to the geometrical changes induced by strain. Gauge factors, TCR, TCGF, and stability of thick-film resistors are compared in Table I with those of strain gauge resistors, as reported in the literature.

A comparative evaluation shows that thick-film resistors have competitive performances with respect to strain gauges usually employed. In fact, even though inferior to the characteristics of semiconductor strain gauges with regard to strain sensitivity, they have lower TCR and TCGF; on the other hand, thick film resistors appear more sensitive than metal resistors with comparable TCR and TCGF. Moreover, thick-film stability is better than that of discontinuous metal films and of evaporated or sputtered cermet resistors, with the same sim-

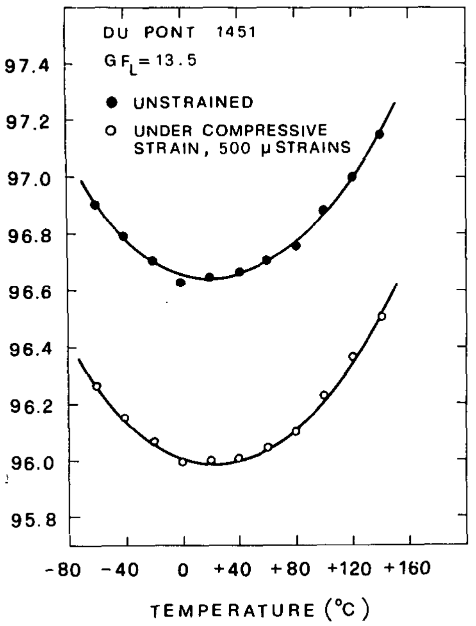

Fig. 3. Temperature dependence of resistance in strained and unstrained Dupont 1451 resistors (100 kΩ/□).

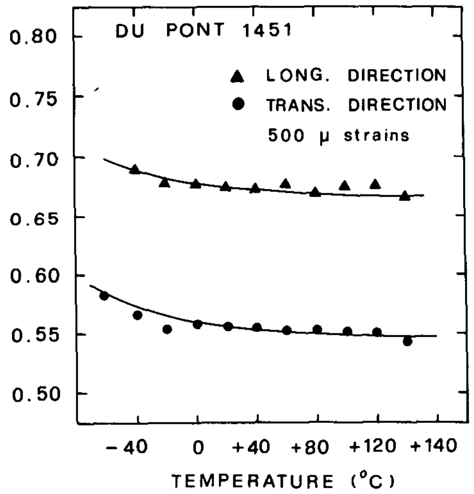

Fig. 4. Temperature dependence of longitudinal gauge factor in a Dupont 1451 thick-film resistor.

plicity of preparation. All these characteristics can be of interest for the application of thick-film resistors as strain sensors in force, pressure and torque measurements.

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TABLE I
PROPERTIES OF MATERIALS FOR STRAIN GAUGE APPLICATIONS

Material	GF	TCR ppm/°C	TCGF ppm/°C	Time stability
Metal wires	2 - 5	20-4000	20-100	very good
Continuous metal film	2 - 5	20-4000	20-100	good
Discontinuous metal film	100	1000	----	worst
Cermet	100	1000	----	poor
Semiconductor	40-175	400-9000	200-5000	good
Thick film resistors	10-15	100	< 500	good

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