

A THICK FILM SENSING ELEMENT FOR TRUE RMS METER

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A sensing element for true RMS meter was realized in thick film technology. The temperature gradient along a substrate was measured by thick film thermocouples, based on a combination of Pt/Ag-Pd/Ag, Pt/Au-Au and Ni-Cr. A voltage response of the element was measured as a function of the current through the heating resistor at different ambient temperatures. The transfer function $K(T)$ of the RMS meter was found to be relatively independent of ambient temperature, which means that the voltage response is usably linear.

An element for measuring the root mean square (RMS) of the current or voltage¹ was realized in thick film technology. The meter averages variable power $(I(t)^2$ or $U(t)^2$) dissipated in a resistance load with a time constant of a few tens of seconds. A suitable application of this “heat method” of integration is a transducer for discontinuous power regulation; for example, switching mode regulation.

The sensing element for RMS meter is schematically presented in Fig. 1. A thick film resistor (heater) is printed and fired on one side of a ceramic substrate. The power dissipated in the heating resistor, which is proportional to I^2 or U^2 causes a thermal gradient along the length of the substrate. The thermal gradient is measured by thermocouples made from combinations of thick film conductor materials.

The principle of operation is expressed by the following equations:

$$P = I^2 \times R = (\lambda \times A \times \Delta T)/L \quad (1)$$

where: P = power (W)
 R = resistivity (ohm)
 λ = heat conductivity (W/mK)
 A = transverse section of substrate (m²)
 L = length of thermocouples (m)
 ΔT = temperature difference between hot and cold junction of thermocouples (K)

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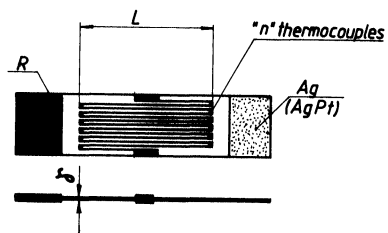


FIGURE 1 An experimental prototype of a thick film sensing element for RMS meter. On one side of the Al_2O_3 substrate is the heating resistor, the other side is metallized with Ag/Pt or Ag/Pd conductor for soldering it into a heat sink. The output voltage U is generated by the temperature difference between the hot and cold junction.

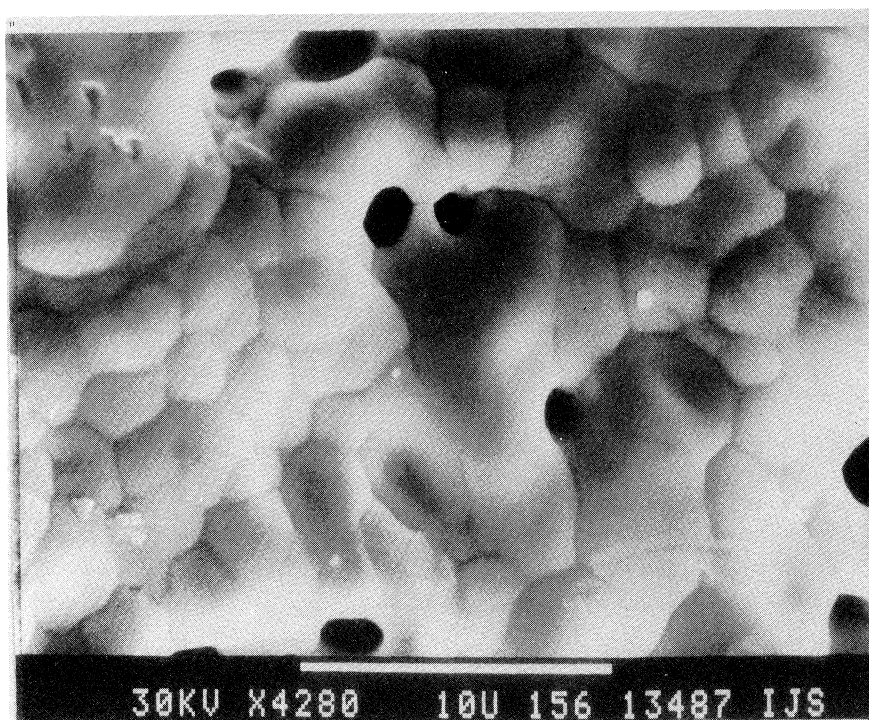


FIGURE 2 Microstructure of gold paste, fired at 850°C , $\times 4280$.

The output voltage (EMF) of the thermocouples is proportional to the temperature difference between the hot and cold junction:

$$U_T = k_T \times \Delta T \quad (2)$$

where: U_T = output voltage of thermocouple (V)
 k_T = sensitivity of voltage response (V/K)

The voltage response of an element with “n” thermocouples is obtained by combining eqs. (1) and (2):

$$\begin{aligned} U_T &= (I^2 \times L \times R \times k_T \times n) / (A \times \lambda) = \\ &= I^2 \times K(T) \end{aligned} \quad (3)$$

where: $K(T)$ = transfer function (V/A^2)

The transfer function $K(T)$ is temperature dependent because the heat conductivity of the ceramic, the voltage response of the thermocouples and, to a lesser degree, also the sheet resistivity of the heating resistor are temperature dependent. It is desirable, however, that the temperature dependence of the transfer function is small so that the voltage response of the sensing element for RMS meter is as linear a function of I^2 as possible.

Experimental prototypes of the thick film sensing element RMS meter were made on $50.8 \times 12.7 \text{ mm}^2$ ($2'' \times 1/2''$) 96% Al_2O_3 substrates. The thermocouples were made from Pt/Au-Au, Pd/Ag-Pt/Ag and Ni-Cr paste combinations. Noble metal conductors (Du Pont) were fired at 850°C , while air-firing Ni and Cr pastes (Electro Science Labs.) were fired at 750°C . Twelve thermocouples were printed and fired on both sides of the substrate and connected over the edge to attain the higher output voltage. In the case of non-solderable Ni and Cr conductors, silver paste was used for terminations. Heating resistors were made of HS-8011 resistor paste (Du Pont) with a nominal sheet resistivity 10 ohm/0 ohm/ which is a stable material with temperature coefficient of resistivity below $100 \times 10^{-6}/\text{K}$. The heating resistor and thermocouples were protected by low firing temperature (525°C) glass protection.

Sample microstructures of conductors are shown in Fig. 2 (Au paste), Fig. 3 (Cr paste) and Fig. 4 (Ni paste). The microstructure of the gold paste (Fig. 2) is an example of a typical microstructure of noble metal metal thick film conductor. The material is densely sintered with few pores. Grain size varies between 2 and 10 μm . On the other hand, the Cr based material (Fig. 3) consists of small, irregular grains covered with an oxide “skin”. The oxide layer on the metal grains is probably responsible for the poor sintering and absence of grain growth during firing. The structure of the Ni paste (Fig. 4) is covered with “splashes” of glass phase (the main components of the glass phase, as revealed by energy dispersive X-ray analysis, are PbO , Al_2O_3 , SiO_2 and probably also B_2O_3 , which can not be detected by EDX). The high concentration of the glass phase is probably added to overcome the poor sinterability of Ni powder at this relatively low firing temperature (750°C). The oxidation of the Cr grains and the glass on the surface of the Ni film are the reasons for the non-solderability of these two materials.

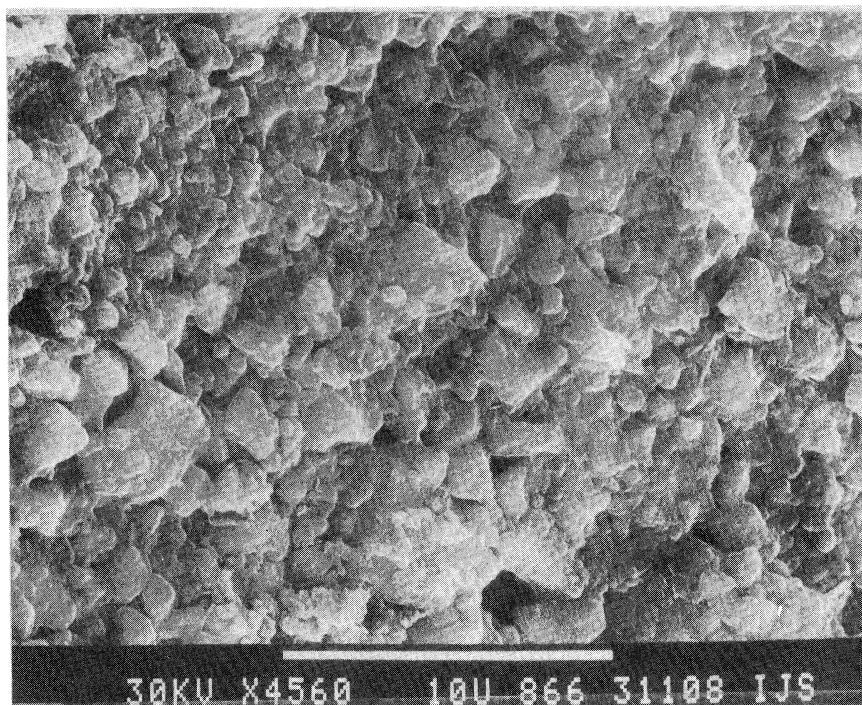


FIGURE 3 Microstructure of chromium paste, fired at 750°C. The structure is poorly sintered due to surface oxidation of metal grains, $\times 4560$.

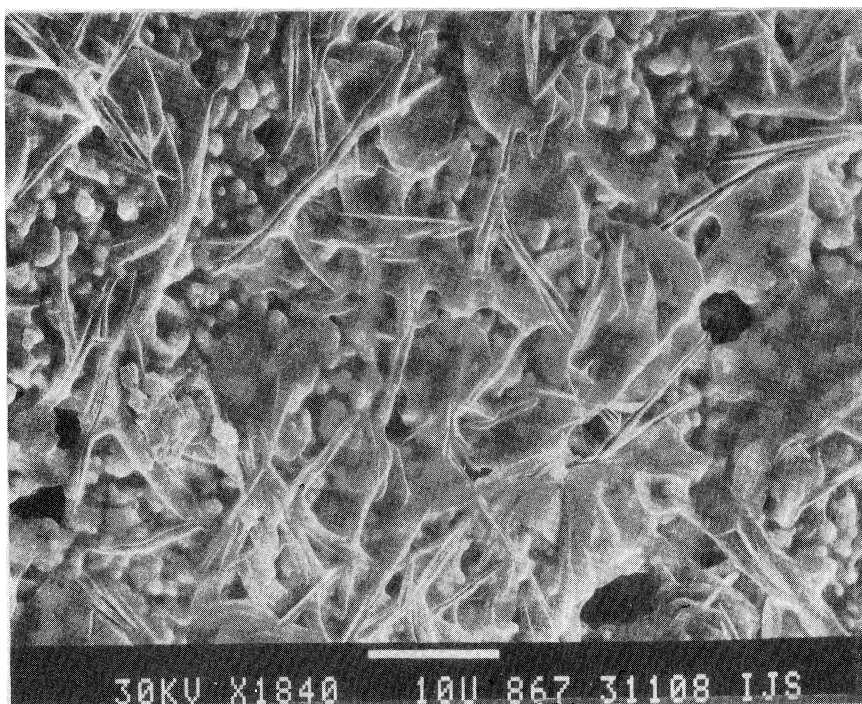


FIGURE 4 Microstructure of nickel paste, fired at 750°C. The surface is covered with "splashes" of glass phase, $\times 1840$.

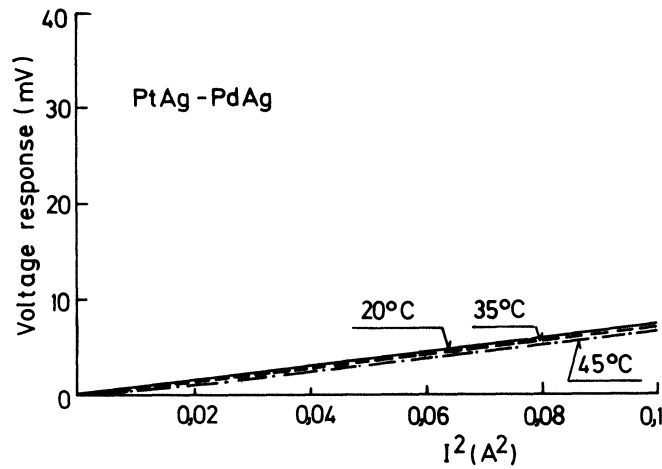


FIGURE 5 Voltage response of sensing element for RMS meter as a function of I^2 and the ambient temperature (20, 35 and 45°C); the thermocouple combination is Pt/Ag-Pd/Ag.

The voltage response of the sensing element was measured at ambient temperatures of 20, 35 and 45°C for currents between 50 and 400 mA. Output voltages are shown in Fig. 5 (Pt/Ag-Pd/Ag combination), in Fig. 6 (Pt/Au-Au combination) and in Fig. 7 (Ni-Cr combination). Thermocouples made from Pt/Ag-Pd/Ag exhibit the lowest voltage response, around 7.5 mV for a current of 320 mA. At the same current value the voltage response of the Pt/Au-Au combination was around 29 mV, and that of Ni-Cr combination

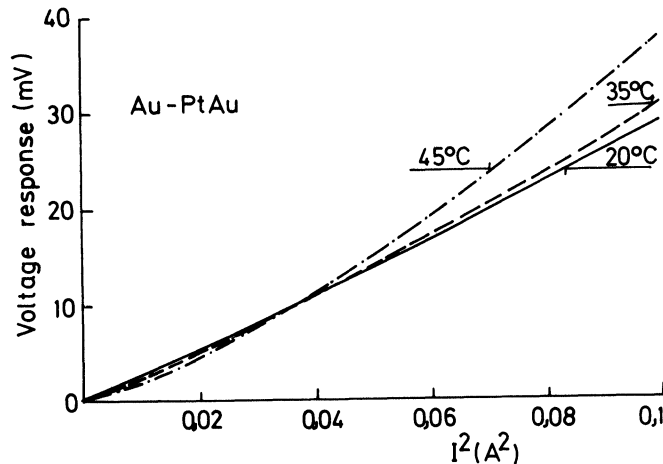


FIGURE 6 Voltage response of sensing element for RMS meter as a function of I^2 and the ambient temperature (20, 35 and 45°C); the thermocouple combination is Pt/Au-Au.

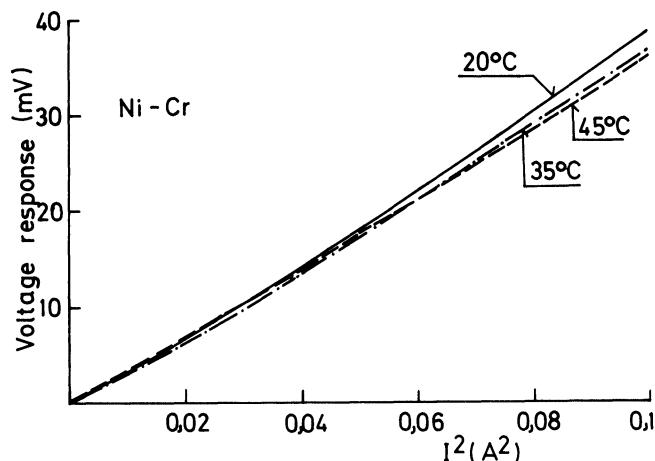


FIGURE 7 Voltage response of sensing element RMS meter as a function of I^2 and the ambient temperature (20, 35 and 45°C); the thermocouple combination is Ni-Cr.

around 38 mV. It can be seen that voltage response of Ni-Cr thermocouples is higher than that of Au-Au/Pt thermocouples. The use of Ni-Cr thermocouples in a sensing element for RMS meter would also lower the production costs as the price of Ni and Cr thick film pastes is much lower than that of gold and gold alloys and is similar to the price of Pd/Ag materials.

The average value of the transfer function $K(T)$, expressed in (mV/A²) as a function of ambient temperature is presented in Fig. 8. The transfer function increases with

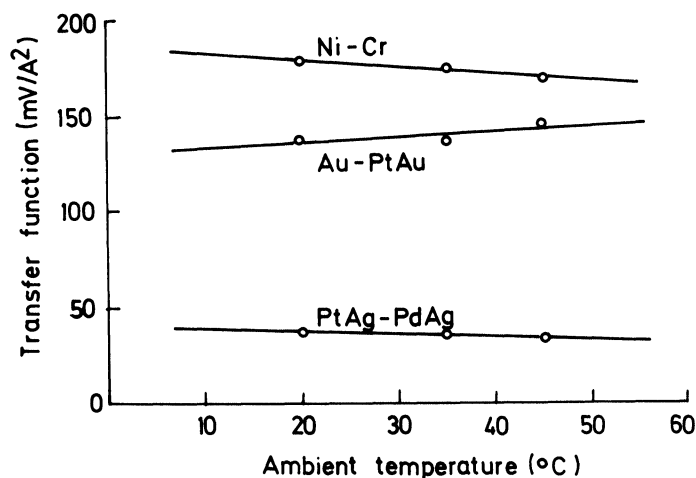


FIGURE 8 The average value of the transfer function $K(T)$ vs. ambient temperature.

increasing temperature for the Pt/Au-Au combination and with decreasing temperature for Pt/Ag-Pd/Ag and Ni-Cr combination. However, this temperature dependence is relatively small, which means that the voltage response of sensing element for RMS meter is usably linear.

To increase the voltage output several substrates could be connected. With a proper choice of heating resistor resistivity, a sensing element for true RMS meter for currents from a few mA to a few A could be realized. For higher currents a shunt resistor could be used.

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