Modelling of Temperature Coefficient of Resistance of a Thin Film RTD Towards Exhaust Gas Measurement Applications

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Abstract—Current research in the automotive industry sector focuses on the application of platinum thin film sensors for exhaust temperature measurement. The prime intention of this paper is to pioneer the design and development of Platinum/Rhodium (Pt/Rh) sensors for exhaust gas temperature measurement. The developed sensors were able to endure harsh temperature environments (up to 950°C). In addition, the Pt/Rh sensors resistivity response to temperature increase was described by a second order polynomial characteristic equation. This equation can be stored in the electronics incorporated in the engine management system. Therefore, the resistance reading of the Pt/Rh sensor in the exhaust system can be decoded as a temperature measurement.

Keywords—exhaust gas measurement; RTD; Pt/Rh sensors; temperature coefficient of resistance.

I. INTRODUCTION

Recently, emissions regulations have become more firm for motor vehicles as technology has improved. Automotive industries are working towards the improvement of existing control technologies and developing new emissions devices. Certain new emissions devices are very sensitive to temperature as they are inactive below specific temperatures, and cannot survive at higher temperatures. Examples of such devices including Diesel Particulate Filters (DPF), Selective Catalytic Reduction (SCR) and Diesel Oxidation Catalysts. Therefore, temperature measurement on these devices has become more vital.

It has been difficult to produce an instrument stable at the harsh environments encountered for the automotive applications. High temperatures at the exhaust and high centrifugal forces are not the only complications however, the corrosive exhaust gases and high velocity of the particulates can also cause potential damage to the sensing element. In this paper, the potential of Resistance Temperature Detector (RTD) for the measurement of harsh temperature environments have been discussed. RTD is a positive temperature coefficient device, in which resistance increases with temperature. Platinum is one of the common RTD materials with a temperature coefficient of $0.00385 \, \Omega/\Omega/°C$ and practical temperature range of -200°C to 600°C and can be extended to 1000°C. Though, Platinum is the primary choice in RTD for most industrial, commercial, laboratory and other critical temperature measurements the other RTD materials used are Copper [1, 2], nickel [3, 4] and nickel iron alloys. However, platinum is the metal of choice for producing thin film RTDs because of its resistance to oxidation, best accuracy and it has chemical and thermal stability among the common RTD materials. In addition, platinum is the only RTD commonly available with a thin film element style to industrial standards.

Many papers reported on the design and development of platinum thin film RTDs and among them few researchers have analyzed the thermal hysteresis effects [5-8], thermal strain effects [9], thin film thickness effects [2], stagnation temperature [10], degradation effects at high temperature [11] and the long term stability [6, 12] of the platinum RTDs. However temperature coefficient of resistance (TCR) plays an important role in determining the sensitivity of the RTD elements as it characterizes the average temperature change of a 1Ω RTD. The focus of this work was therefore to model and optimize the characteristic equation of the temperature coefficient of resistance and to find ways of extending the operating temperature range of Platinum/Rhodium thin film sensors suitable for exhaust gas temperature measurements.

II. EXPERIMENTAL DETAILS

Platinum printing paste was doped with up to 0.05% Rhodium, as weighted %, and screen printed onto fired Aluminum Oxide ceramic substrate to approximately 1.5 micron thickness. Positive resist was spun on and patterned using proximity lithography and the structures developed. Post etching, the individual PT sensor elements were laser trimmed to PT-200 tolerances. Further processing to enclose the sensors with screen printed aluminum oxide and glass layers was performed. Platinum connecting wire was resistively welded...
and enclosed in a glass layer before the substrate was diced into individual PT-200 Platinum/Rhodium sensors.

The individual sensors were then heated in a Julabo chiller unit from 0 to 100 degrees Celsius through a 4-wire bridge circuit and the resistance change measured. A Carbolite oven was used for the temperature range from 100 to 900 degrees Celsius connected to a 3-wire bridge circuit as shown in Fig.1 (to eliminate the connecting wire resistance effect), the bridge voltage was measured and the sensor resistance then calculated.

![Fig.1. 3-wire bridge circuit (R1 = R2 = 470 Ω and R3 = 1k Ω. Vs = 5, 12 or 24 V and Rx is the RTD element).](image)

**III. RESULTS AND DISCUSSION**

Addition of fraction of impurities in the form of alloying metals has a potential to affect the value of TCR. Therefore, alloys of platinum used to provide the desired TCR has a great significance in the design of thin film RTD. The desired characteristic value of the TCR is 0.00385 Ω/Ω/°C and it has been the industrial standard, which is slightly below the TCR for very thick films/ wire of pure very less defect platinum (0.003923 Ω/Ω/°C). The control of the variables that contribute to the decrease of the TCR is very challenging and only very few techniques are available to deposit metal films with a controlled TCR value. It is the aim of this paper to provide a thin film platinum RTD doped with rhodium with a predetermined TCR and determining the effect of rhodium on resistivity and TCR value sensing element by increasing the concentration of rhodium.

The electrical resistivity also increases linearly as temperature increases and this relationship is known as the temperature coefficient of resistance (TCR) and is given in (1).

\[ \rho = \rho_0 (1 + \alpha (T - T_0)) \]  

where \( T_0 \) is the initial temperature, \( T \) the final temperature and \( \alpha \) is the TCR. It is clear from (1) that small change in electrical resistivity is proportional to the change in temperature. TCR can be obtained from a first-order polynomial curve fit equation if the resistivity is graphed over a positive temperature (Celsius) range. However, a second-order polynomial curve fit is typically used to represent the characteristic equation for the RTD.

Here, the Pt sensors resistivity response to temperature increase is described by a second order polynomial characteristic equation (2) and the platinum sensors have an accepted characteristic equation of the form:

\[ \rho = \rho_0 (1 + AT - BT^2) \]  

where \( \rho \) is the resistivity, \( \rho_0 \) the intrinsic resistivity and \( T \) is the temperature in Celsius. This is known as the Callendar – van Dusen equation and describes the relationship between resistance and temperature.

A two dimensional model was created analogous to that proposed by Lacy.F [13] to demonstrate the behaviour of Pt/Rh sensing element. Solid state principles were also used to describe and characterize the electrical resistivity with respect to temperature. For platinum the accepted industry standard TCR is 0.00392Ω/°C. However, the required value of TCR was 0.00381 Ω/°C as the intention of the work was to develop a thin film RTD for exhaust temperature sensing. In addition, a linear response was also expected from -50 to 950 degrees Celsius for a PT-200 RTD. The TCR correction was achieved by doping the platinum with rhodium and linearity was controlled by the in-house processing parameters. Therefore, the required characteristic equation is:

\[ R_T = R_0 (1 + AT - BT^2) \]  

where \( A = 3.8684 \times 10^{-3} \) and \( B = 5.8125 \times 10^{-7} \). \( R_T \) is the resistance of the Pt/Rh sensor at temperature \( T \) and \( R_0 \) is the resistance at zero degrees Celsius.

In order examine the processing and manufacturability of the designed Pt/Rh sensors, the experimental data must coincide with the characteristic equation. In this paper, we test this characteristic equation. In contrast, the performance of the developed Pt/Rh sensors was evaluated with the theoretical solid state model [13] over the range of 0 to 900 degrees Celsius. The results obtained from the temperature investigation are shown in Fig.1. The polynomial correlation of \( R^2 = 0.999999999930 \) was observed in Fig.2 and its corresponding fit line equation is given in (4).

\[ R_T = -0.000115404412T^2 + 0.767901722755T + 198.499279532699 \]  

**Results and Discussion**
The required resistance for the process was of 198.5 Ω at 0 degrees Celsius. The value obtained from the experimental data was in strong agreement as well. The second order polynomial (4) was employed in the correct format which in turn returned the characteristic equation specified for the manufacture (5).

\[
\frac{\rho}{\rho_0} = -0.000000581382T^2 + 0.003868522533T + 0.999996370442
\]  \hspace{1cm} (5)

Fig. 3 shows the response of TCR x ΔT against temperature in degrees Celsius and again a linear response was obtained with respect to the TCR of 3810 PPM.

The experimental data showed that the sensor produced methe requirements from the response and functionality bases. Consequently, the model produced by Lacy. F [13] was applied to the same results. The equation for electrical resistivity as a function of temperature for the two-dimensional face centered cubic model which represents the atoms of the conductor is given in (6).

\[
\rho = \rho_0 \left[ \frac{1}{2a + b} \left( \frac{T}{T_2} - 1 \right) \right] + 1 \right] \right] \right] \]  \hspace{1cm} (6)

Where, \( a = 1 \times 10^{-12} \text{ m} \), \( b = 3.92 \times 10^{-10} \text{ m} \), \( k = 8.617 \times 10^{-5} \text{ } \), \( T = 273 \text{ } \), \( T_1 = 2.005 \text{ with } T_2 = 1 \text{ and } \gamma = (\frac{5.39 \times 10^{-33}}{6.24 \times 10^{18}}) \text{ J m} \).

The values of the parameter for (6) was predominantly developed for pure platinum by [13]. It is experimentally evident that the electrical resistivity of thin-film platinum RTDs in particular does not behave exactly as bulk materials. Due to the reason, that the mean free path of electrons in nanosized conductors is smaller compared to electrons in bulk conductors. Here, the value of \( \gamma \) in (6) as one of the control variable was varied accordingly from the bulk value to simulate thin-film conditions.

Lacy’s model describes a quantum mechanical version of the standard second order polynomial characteristic equation for resistivity response against temperature. This model was applied to the raw experimental data and the results obtained are shown in Fig. 4. The best fit line showed a correlation of \( R^2 = 0.9999999835 \) and returned (7).

\[
\rho(T) = -0.0000229505T^2 + 0.4876336188T + 135.1721950209
\]  \hspace{1cm} (7)

Putting this in the correct format provides,

\[
\rho(T) = -0.000000581366T^2 + 0.003868504198T + 1.00000000000
\]  \hspace{1cm} (8)

This shows that the required characteristic equation for Pt/Rh sensors was again returned and agrees well with the conclusions put forward by [13]. In addition to the responses for Pt/Rh sensor obtained using (6) that exhibited resistivity-temperature profiles, the TCR value also coincides with experimental results. Therefore, the results obtained with the two-dimensional model are in conformity with experimental findings.

Fig. 4. A best fit line for our raw data using the model described by [13].
The values of the parameter for the Lacy’s [13] model were developed for pure platinum and designed to show a linear response over the range of -200 to 650 degree Celsius. Here, it has been proved that this model is valid for platinum doped with rhodium and for elevated temperatures up to 900 degree Celsius.

However, the results demonstrated are for platinum doped with 0.05% of rhodium. Therefore, the effect of the rhodium on the overall model is very small. This can be explained by applying Mathieson’s rule to the overall composition. Matthiessen’s rule indicates that defects and impurities possibly could constitute for additional components however, these are small contributions and has no influence at higher temperatures. On the other hand, this will produce significant error at lower temperature values. It can be concluded that the effect of the phonon vibrations of the platinum atoms far outweighs the 0.05% rhodium and as result a very small effect of the resistivity by the additional rhodium is expected.

However, it has been observed that the TCR is affected by doping platinum with rhodium.

IV. CONCLUSION

Platinum thin film sensors were manufactured using screen printing of platinum paste slightly doped with rhodium. These sensors showed a strong correlation to the theoretical expected second order polynomial equation that describes the response of resistivity of platinum to temperature. It has been showed that the quantum mechanical model of this response is also valid for screen printed platinum/rhodium sensors in the range of 0 to 900 degree Celsius and this agrees well with the arguments put forward by Lacy. F[13]. The value of the parameters for bulk platinum also holds in the quantum mechanical equation for the developed thin film platinum/rhodium sensors. This offers a good insight into the phonon vibration interaction with passing electrons for the explanation of the resistivity increase with temperature. It has been observed that addition of the rhodium as a potential impurity will affect the scattering of electrons. This effect is so small and has no detectable effect on overall resistivity hence can be excluded in the resistivity analysis. However, the addition of rhodium has a strong influence on the TCR in the PPM range.

Further work will be focused to model and optimize the characteristic equation of the pre-determined TCR with an extent of temperatures from -40 to 950 degree Celsius with a four-wire bridge circuit.

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