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Investigating Thin Films for Use as Temperature Sensors

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Abstract—**Platinum films are being successfully used as temperature detectors for sensors and sensor networks. Although metals have a well characterized temperature-resistance relationship, this relationship will change if one of the dimensions of the material is nanometer sized. Experiments were performed to determine this relationship when thin films (of nanometer thickness) of platinum are sputtered on a glass substrate. Results indicate that the resistance of the thin films is linearly related to temperature below a certain temperature, however, above this temperature, the resistance remains relatively constant as temperature increases.**

Index Terms—**detector, nanomaterial, resistance, temperature, thin film**

I. INTRODUCTION

Fabricating thin films has become routine due to the well-established photolithographic processing involved. These films can be conductors, semiconductors, or insulators. Thin films find uses in various fields such as optics, semiconductor electronics, micro-electro-mechanical-systems (MEMS), corrosion, nanotechnology, biomedical sciences, and sensors.

It is being recognized that materials exhibit different properties or characteristics when their dimensions decrease to submicron size. Characteristics such as wavelength absorption and scattering, electrical and thermal conductivity, bandgap spacing, and melting temperature are some of the material properties that are affected by reducing dimensions. Metals or conductors have well characterized bulk resistive properties that are predictable and follow a standard equation (the resistance depends on the material dimensions and the resistivity which is a proportionality 'constant'). Research is showing that if the metal is made sufficiently thin, the electrical resistance of the conductor does not have the predictable response because the material's resistivity is not constant, but dependent on the conductor's thickness.

Barnat et al. have shown that the electrical resistivity of thin films of copper has a dependence on the thickness of the film provided that the thickness is below the bulk mean free path for electrons [1]. Similarly, Jen et al. studied metallic films composed of palladium, gold, and copper and found that mean free path of electrons as well as surface roughness could play a role in determining the resistivity of the metallic film [2]. They showed that the resistivity for gold and copper significantly increases if the film thickness falls below about 30 nm. Additionally, Rossnagel et al. found that the resistivity of thin copper films becomes dependent on film thickness as the dimensions approach the electron mean-free-path [3]. The key contributions are from electron–surface scattering, grain boundary scattering, and surface roughness-induced scattering. W. Zhang et al. also show that the resistivity of thin metal films exhibit a high dependence upon their thickness due to the mean free path of electrons [4]. However, they notice that the fabrication or deposition method also have an effect on the resistivity at these dimensions.

Fan et al. developed a model in which includes electron scattering from the metallic film surfaces and grain boundaries [5]. Their theoretical results seem to correlate quite well with experimental data. Yarimbiyik et al. developed a computer simulation program to model various parameters that could affect the electrical resistance of thin metal films [6]. They show that a change in resistivity with temperature begins to increase as dimensions approach the bulk mean free path of the electrons in the metal. Kawamura et al. showed that the temperature coefficient of resistance (TCR) for sputtered platinum films is a function of temperature [7]. Specifically, they showed that as the film thickness increases from 0.4nm – 600nm, the TCR increases as well. X. Zhang et al. provide experimental results that show that the electrical conductivity and the TCR of nanofilms are greatly lower than the corresponding bulk values for temperatures from 77 to 330 K [8, 9].

It is known that the electrical resistance, of a material is proportional to the length and resistivity of the material and inversely proportional to the cross sectional area of the material. In equation form, this is given by Equation 1.

$$R = \rho \frac{l}{A} \qquad (1)$$

Furthermore, the resistivity of a material is a function of temperature as given by Equation 2

$$\rho = \rho_0 \left[1 + \alpha \left(T - T_0\right)\right] \qquad (2)$$

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where α is the TCR, T is the temperature, and ρ_0 is the resistivity at temperature T_0. So, it is easy to see that the change in resistance of a material is proportional to its change in temperature as given in Equation 3.

$$\frac{\Delta R}{R_0} = \alpha \Delta T \qquad (3)$$

Therefore, based on these equations and the aforementioned research, for a given temperature change, the change in resistance of thinner films is expect to be smaller than for thicker films.

The research results provided in this paper will describe the fabrication of thin films of platinum and show the resistance of these films as a function of temperature. The film thickness ranges from 46.3nm to 92.6nm and the temperature ranges from 25^{o}C to 150^{o}C.

II. EXPERIMENTAL PROCEDURE

A. *Device Fabrication*

The thin film platinum temperature sensors were fabricated using the following procedure (as illustrated in Fig. 1). A glass substrate was first cleaned with acetone and isopropyl alcohol. Then S1805 photoresist was deposited on the substrate by spinning at 3550 r.p.m. for 20 seconds. Then, these substrates were soft baked for 4 minutes in an oven at a temperature of 100º C.

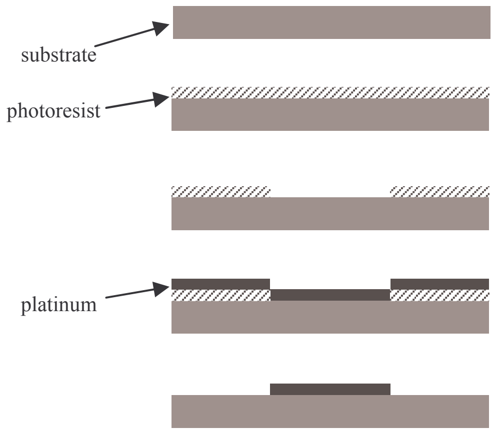


Fig. 1. Diagram of the fabrication processing steps.

Then the substrate was patterned using photolithography. A photomask was placed over the sample and then exposed to 22 mJ/cm2 of ultraviolet radiation for 8 seconds. Next, the unwanted photoresist was removed by immersing the substrate in MF-CD-26 developer for approximately 2 minutes. Then the substrate was rinsed with water to remove the developer. Subsequently, DC sputtering was used to deposit the desired thickness of platinum onto the substrates. After the platinum was deposited over the entire surface of the substrate, the unwanted platinum was removed through liftoff by rinsing the substrate with acetone for approximately 10 seconds until only the patterned platinum remained. Again, the fabrication steps are shown schematically in Fig. 1.

After the processing steps have been completed, the structure that appears on the glass substrate is a serpentine shape as shown in Fig. 2.

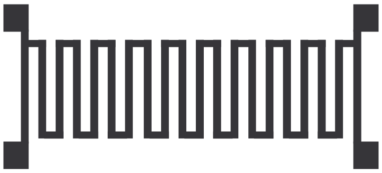


Fig. 2. Top view of the pattern on the glass substrate.

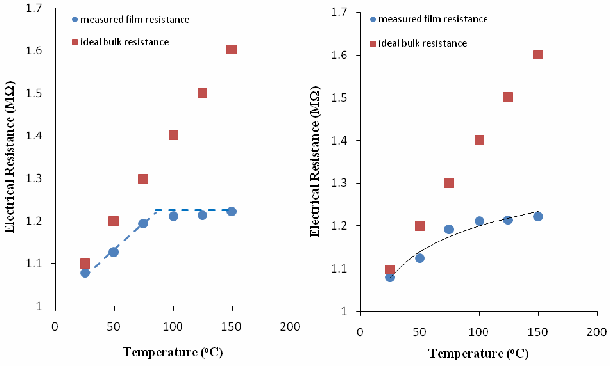
B. *Measurements*

The thin film sensors were used to detect temperature via measurements of electrical resistance.

The sensors (of varying thicknesses) were placed in an oven/furnace and the temperature was set to the desired level. Upon stabilizing at this temperature, the electrical resistance of the sensors was measured with a digital multimeter. The temperature was varied from 25^{o}C to 150^{o}C and resistance values were recorded over this temperature range.

III. RESULTS

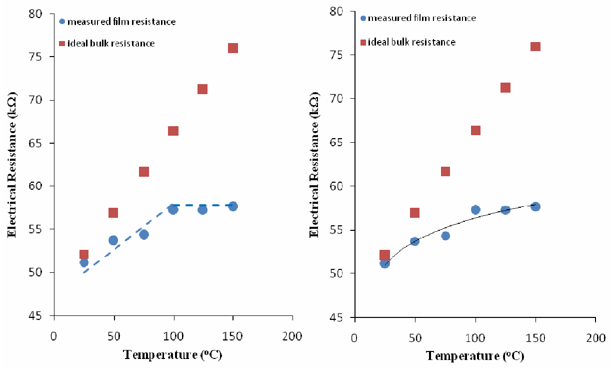
The electrical resistance vs. temperature for the 46.3nm thin film is shown in Fig. 3. This graph provides the experimental measurements of the resistance as well as the resistance that would theoretically be obtained for platinum in bulk form.



(a) (b)

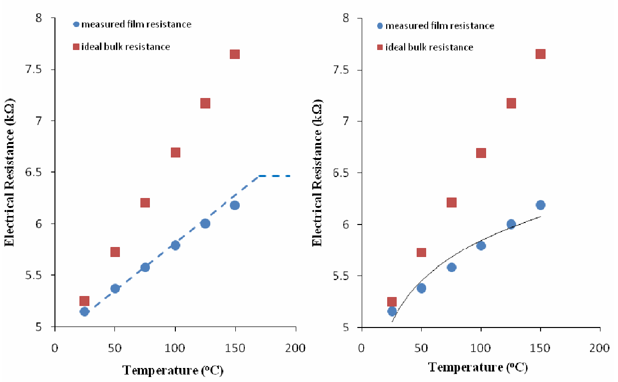
Fig. 3. Graph of the measured electrical resistance vs. temperature for 46.3nm platinum film showing (a) 'saturation' level, and (b) logarithmic curve fit. Also shown in each is the ideal resistance that would be obtained for bulk platinum.

Likewise, results are shown in Figs. 4 and 5 for temperature sensing thin film of 74.0nm and 92.6nm, respectively.



(a) (b)

Fig. 4. Graph of the measured electrical resistance vs. temperature for 74.0nm platinum film showing (a) 'saturation' level, and (b) logarithmic curve fit. Also shown in each is the ideal resistance that would be obtained for bulk platinum.



(a) (b)

Fig. 5. Graph of the measured electrical resistance vs. temperature for 92.6nm platinum film showing (a) estimated 'saturation' level, and (b) logarithmic curve fit. Also shown in each is the ideal resistance that would be obtained for bulk platinum.

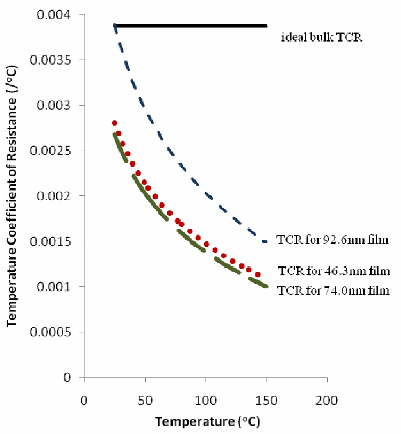


Fig. 6. Graph of the temperature coefficient of resistance vs. temperature for the thin films and for the ideal case of bulk platinum.

Using a logarithmic curve fit for the measured resistances [as shown in Figs. 3(b), 4(b), and 5(b)], the temperature coefficient of resistance (TCR) can be calculated for each of the thin films (using equation 3). The results are graphed and the curves are shown in Fig. 6.

IV. DISCUSSION

It is seen from the resistance vs. temperature graphs that all of the films exhibit a resistance below the ideal bulk resistance over the entire temperature range. Fig. 3(a) shows that for a film thickness of 46.3nm, there is very little change in the resistance once the temperature exceeds 85°C. Similarly, from Fig. 4(a), a film with a thickness of 74.0nm will have a significantly smaller change in resistance after the temperature rises above 100°C. Whereas the 'transition temperature' (or the temperature where the resistance does not significantly increase for further increases in the temperature) can be clearly recognized from the graphs in Figs. 3(a) and 4(a), this value for the 92.6nm platinum film cannot be easily discerned from the graphed data in Fig. 5. Undoubtedly, this transition temperature occurs beyond the maximum temperature level used in this research (i.e., 150°C), so an estimated saturation level is depicted in Fig. 5(a).

Logarithmic curve fits provided a good and logical correlation between the resistance and temperature for the smallest film thicknesses (for 46.3nm, $R^2 = 0.9548$; for 74.0nm, $R^2 = 0.9485$). The same type of fit was applied to the 92.6nm film thickness and it was found that a similar correlation of $R^2 = 0.9463$ resulted. Although the data for the 92.6nm thin film looks "linear" over the 25°C to 150°C temperature range, it is believed that it would follow the same trend as the two thinner films if measurements were recorded at higher temperatures (and thus, a logarithmic curve fit was used).

Based on the measured resistance data, temperature coefficient or resistances were calculated for each film thickness using Equation 3. The data was then fit with the best curve and results are shown in Fig. 6. This figure shows the calculated TCR for the three thin films (along with the ideal bulk TCR). All three of these temperature coefficients follow logarithmic curves. For thin films of thicknesses 46.3nm and 92.6nm, the correlation coefficient is $R^2 = 0.998$, and for film thickness 74.0nm, the correlation is $R^2 = 0.997$. Thus, the curves fit the measured data really well.

From Fig. 6, several observations can be made. One such observation is that at a particular temperature the two thinnest films have a noticeably lower TCR than the largest film. It is believed that the two thinnest films have approximately the same TCR (due to reasonable measurement error), and thus as the film thickness increases, the TCR increases and will eventually equal the ideal bulk TCR. The other observation is that for a particular film thickness, the TCR decreases as the temperature increases. In other words, a fabricated film that is designed to measure temperature through its resistance will eventually reach a 'saturation point' and not respond (or not respond very well) to further changes in temperature.

This work provides results that are consistent with the work from other research groups. Several groups have shown that the resistivity (and thus the resistance) of metallic thin films will be different from their 'bulk' values if the films have dimensions on the order of the electron mean free path (i.e., in the nanometer range). The platinum films used in this work were in the nanometer range and it was found that the resistance of each film was always less than its corresponding ideal bulk value. Additionally, research groups have shown that the TCR of metal thin films will vary if the temperature or film thickness changes. Results are provided in this paper that support this referenced work. Figs. 3 and 4 show clearly that the resistance of the films does not change as dramatically if the temperature goes beyond a certain point. Moreover, Fig. 6 shows directly that the TCR is a function of temperature and film thickness.

V. CONCLUSION

In conclusion, this work shows that thin platinum thin films can be used as temperature detectors by measuring the electrical resistance of the film. However, when the films are nanometer sized, care must be taken in 'predicting' the temperature that caused/created that measured resistance. Additionally, if the sensors will be used in a place where the temperature measurement range is known, proper design can be performed to achieve sufficient output from the thin film sensor.

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