PHYSICAL PROPERTIES OBTAINED FROM MEASURED THERMAL PROFILES IN THE FILM/SUBSTRATE BIMATERIAL SYSTEM

R. D. MALDONADO∗, A. I. OLIVA∗†,‡ and H. G. RIVEROS∗§,

∗Centro de Investigación y de Estudios Avanzados del IPN, Unidad Mérida,
Depto. de Física Aplicada, Km. 6 Ant. Carr. Progreso,
A.P. 73-Cordemex, 97310 Mérida Yucatán, México
†Instituto de Física, UNAM, A.P. 20-384, 01000, México D.F.
‡oliva@iode.cinvestav.mx
§riveros@fisica.unam.mx

Received 25 January 2006

The microelectronic devices are formed by a substrate that supports the functional thin film material. The thermal, electrical, and mechanical properties of the system depend strongly on the interfacial properties between a film and a substrate. The interfacial nature in a film/substrate system originates the thermal contact resistance (Rtc). We discuss the thermal and the electrical behavior in a film/substrate system (bimaterial system) making emphasis on the Rtc of the interface. Au/glass samples with different thicknesses were prepared by thermal evaporation for experimentation. The bimaterial system was heated by a DC electrical current to obtain thermal profiles. Film and substrate thermal profiles acquired with high resolution combined with a developed bimaterial model are used as an alternative method to estimate the Rtc value at atmospheric pressure, the electrical resistivity ρ, and the thermal resistive coefficient αr in the bimaterial system. The calculated Rtc values ranged from 7.7 × 10⁻⁴ to 1.2 × 10⁻³ m²K/W for the Au/glass system, in good agreement with previously reported values. The ρ values obtained from the thermal profile data present a more reliable value due to the global character than the local values measured by the four-probe technique. Dependence on film thickness was also found in the αr coefficient determination.

Keywords: Thermal resistance; metallic films; bimaterial system; electrical resistivity.

1. Introduction

The new challenges in the materials science have focused on the thin film applications by their newly found promising physical properties and the great advantages of the miniaturization. Different properties have been found on films for small thickness dimensions. Thus, new efforts need to be done in order to investigate about the possible applications and new techniques need to be developed for characterization. However, small thickness dimensions on thin films obligate to include a film support (substrate) such that the combined properties will depend on the support characteristics. A first problem is to separate the film properties from the substrate properties, given that the observed properties acting during work are due to the film/substrate combination. First efforts were made on metallic films/glass substrate system by Avilés et al., where they used a thermal balance to propose a bimaterial thermal model which includes only conduction and...
convection heat transfer mechanism. An improved bimaterial model including the radiation heat mechanism in order to simulate in a more realistic way the thermal profiles on the bimaterial system was published recently, improving the theoretical approximation with the experimental thermal profiles by about 10%. The thermal behavior of the film/substrate interfaces plays an important role in the performance of nanometer-scale devices, nanolayers, and nanocrystalline materials. Different devices for heat transfer have been studied for improving functionality. Electronic packaging in the PCs tries to remove the heat efficiently from the CPU to the environment through heat sinks by eliminating the microgaps in the interface device-heat sink in order to reduce the $R_{tc}$ value. Nanoscale heat conduction was recently analyzed through multiple tunnel junctions formed by Ta/TaO$_x$ barriers, and it was found that the thermal resistance increases with the thickness barrier. Thermal conductance of epitaxial interfaces was studied on TiN/MgO nanofilms, finding a value five times larger than the highest value reported. Recently, an atomic switch with quantized conductance was developed working at 1 MHz and an operating voltage of 0.6 V by using electrodes with 1 nm apart tunneling current from an Ag$_2$S$_x$ nanoprotrusion. Thus, the great variety of nanodevices can be produced in the future can only be limited by our mind.

In this work we present a methodology to calculate some thermal properties from the combination of a developed bimaterial model and the experimental thermal profiles measured with high resolution in Au film/glass systems. Physical properties such as the resistive thermal coefficient (RTC) $\alpha$, the contact thermal resistance $R_{tc}$, the convection coefficient $h$, and the electrical resistivity $\rho$ are obtained as a function of the film thickness and the substrate characteristics from the thermal profiles.

## 2. Theory

### 2.1. Bimaterial thermal model

Figure 1 describes the bimaterial system analyzed and the thermal and geometrical parameters used for the theoretical analysis. The balance of energy to the complete system needs to obey

$$Q_0 = [Q_1 + Q_h + Q_{film}] + [Q_r + Q_h + Q_{substrate}], \quad (1)$$

where $Q_0 = VI$ is the applied total energy (by Joule effect) to the metallic film which is further divided in the thin film and the substrate material. Each heat transfer mechanism in Eq. (1) is defined as $Q_{ai} = m_i C_{pi} (T_i - T_0)$. $Q_{ai} = h_i S_i (T_i - T_0)$, $Q_{hi} = e_i S_i [(T_i + 273) + (T_0 + 273)] [(T_i + 273)^2 + (T_0 + 273)^2]/(T_i - T_0)$, which are the sensible heat and the heat losses by convection and radiation, respectively.

Subscript $i$ can be changed to 1 for the metallic film and to 2 for the substrate in Eq. (1). Constants $V, I, T_0, T_1, T_2, h_i, S_i, m_i, C_{pi}$, and $\varepsilon_i$ are the voltage, the applied electrical current, the room temperature, the convective coefficient, the area, the mass, the heat capacity, and the emissivity of each component of the bimaterial system, respectively, and $\sigma$ is the Stefan-Boltzmann constant.

We can rewrite the energy balance for thin films and substrates, separately. Only for thin films, the resulting equation is

$$Q_{0} = [Q_1 + Q_h + Q_{film}] + Q_c, \quad (2)$$

where $Q_c = k_2 S_2 (T_2 - T_1)/d_2$, the heat conduction through substrate; $k_2, d_2$, and $T_2$ are the thermal conductivity, the thickness, and the external temperature of the substrate. We are assuming that this last temperature remains constant for the sensible heat calculation. Similarly, for substrates, the heat transfer relation can be calculated by

$$Q_r = Q_{r2} + Q_{r1} + Q_c. \quad (3)$$

Substituting each component of the heat transfer system afore mentioned and redefining a group of variables, we obtain a pair of coupled first-order
physical properties obtained from measured thermal profiles in the film/substrate bimaterial system

differential equations similar to that obtained in Ref. 2, but with the radiation heat transfer included. Uncoupling the differential equations, it is possible to obtain equations to obtain the thermal profiles for films \((X_1)\) and substrates \((X_2)\), respectively. The resulting uncoupled differential equations for \(X_1\) and \(X_2\) are

\[
\frac{d^2X_1}{dt^2} + b_1 \frac{dX_1}{dt} + b_2 X_1 = a_{22} B_0 \quad \text{and} \\
\frac{d^2X_2}{dt^2} + b_1 \frac{dX_2}{dt} + b_2 X_2 = a_{22} B_0,
\]

where subscripts 1 and 2 are used for films and substrates, respectively. Here, variables \(X_1\) and \(X_2\) are defined as a function of time as

\[
X_1(t) = T_1(t) - T_0 = \Delta T_1(t); \\
X_2(t) = T_2(t) - T_0 = \Delta T_2(t).
\]

An important point of the uncoupled differential equations (4) is the second-order character of the resulting equations. Thus, equations obtained correspond to typical equations describing the mechanical harmonic oscillator behavior, where constants \(b_1\) and \(b_2\) are defined as \(b_1 = a_{11} + a_{22}\) and \(b_2 = a_{11}a_{22} - a_{12}a_{21}\), and the other constants are defined as

\[
B_0 = \frac{Q_0}{m_1C_{p1}}; \quad a_{12} = \frac{k_2 S_2}{d_2 m_1C_{p1}}; \quad a_{21} = \frac{k_2 S_2}{d_2 m_2C_{p2}}; \\
a_{11} = \frac{h_1 S_1}{m_1C_{p1}} + \frac{k_2 S_2}{d_2 m_1C_{p1}} + \frac{\sigma_1 S_1 T_0^4}{m_1C_{p1}}; \quad \text{and} \\
a_{22} = \frac{h_2 S_2}{m_2C_{p2}} + \frac{k_2 S_2}{d_2 m_2C_{p2}} + \frac{\sigma_2 S_2 T_0^4}{m_2C_{p2}}.
\]

Note that defined constants \(a_{11}\) and \(a_{22}\) include now the radiation term defined in absolute temperature. Then, the terms \(T_0^4\) and \(T_0^3\) involved in constants \(a_{11}\) and \(a_{22}\) in Eq. (6) are defined as

\[
T_0^4 = [(T_0 + 273) + (T_0 + 273)](T_0 + 273)^2 \\
+ (T_0 + 273)^2 \quad \text{for thin films, and} \\
T_0^3 = [(T_0 + 273) + (T_0 + 273)][(T_0 + 273)^2 \\
+ (T_0 + 273)^2] \quad \text{for substrates}.
\]

Equations (4) were analytically and numerically solved to obtain the thermal profile for films and substrates giving similar results. For films, the thermal profile \(X_1(t)\), with initial conditions \(X_1(0) = 0\) and \(dX_1(0)\) and \(dt = B_0\), is given by

\[
X_1(t) = \frac{a_{22} B_0}{2b_2} \left[ \frac{A}{w} - 1 + \frac{b_2}{a_{22}w} \right] e^{-(A+w)t} \quad \text{and} \\
\frac{a_{22} B_0}{2b_2} \left[ \frac{A}{w} - 1 - \frac{b_2}{a_{22}w} \right] e^{-(A+w)t} + \frac{a_{22} B_0}{b_2},
\]

where

\[
w = \sqrt{\frac{b_1 - 4b_2}{2}} \quad \text{and} \quad A = \frac{b_1}{2}.\]

For substrates, the thermal profile \(X_2(t)\) obtained with initial conditions \(X_2(0) = 0\) and \(dX_2(0)/dt = 0\) is given by

\[
X_2(t) = \frac{a_{22} B_0}{2b_2} \left[ \frac{A}{w} - 1 \right] e^{-(A+w)t} \quad \text{and} \\
\frac{a_{22} B_0}{2b_2} \left[ \frac{A}{w} - 1 \right] e^{-(A+w)t} + \frac{a_{22} B_0}{b_2}.
\]

Note that solutions (8) and (9) give us the thermal profiles with time and their plotting requires an iterative method due to the heat radiation term involved.

2.2. Thermal contact resistance \((R_{tc})\)

Normally, the thermal contact resistance \(R_{tc}\), in the film/substrate interface is defined as the ratio between the change of temperature \((\Delta X_1)\) through the interface of area \(A\) and the conduction heat flow \(Q_0\), that is,

\[
R_{tc} = \frac{\Delta X_1}{Q_0},
\]

Here, the heat conduction considered in solutions (8) and (9) is the flow of energy from the metallic film and transferred to the substrate via the interface. Neglecting the border effects and taking stability conditions, the change of temperature in the film/substrate interface can be written as \(\Delta X_i\). This conduction heat is transferred to the substrate due to its thermal conductivity \(k_s\). Assuming that the film heat is completely transferred to the substrate, the

\[
Q_0 = \frac{\epsilon S_1 \Delta X_1}{\delta} = \frac{k_2 S_2 \Delta X_i}{d_2}.
\]

Here, \(\Delta X_i\) is the change of temperature in the substrate. \(S_1\) and \(S_2\) are the film and substrate areas, \(\delta\) is the interface thickness, and \(\epsilon\) is the thermal contact conductivity of the interface. From Eq. (11),

\[
\Delta X_1 = Q_0 \delta / k_2 S_1 \quad \text{and} \quad \Delta X_i = Q_0 \delta / k_2 S_2; \quad \text{thus, the}
\]
total change of temperature from the interface to the substrate is given by

$$\Delta X = \Delta X_1 + \Delta X' = Q_1 \left( \frac{d_2}{k_2 S_2} \right)$$

(12)

Here, parameter $k_e$ is called the effective thermal conductivity of the substrate, and we are assuming that $\delta \ll d_2$. By considering $S_1 = S_2$, we finally obtain from Eq. (12) the $R_{tc}$ value, i.e.,

$$R_{tc} = \frac{d_2}{k_e} \cdot d_2 \left( \frac{1}{k_1} - \frac{1}{k_2} \right).$$

(13)

Equation (13) represents a simple way to measure the $R_{tc}$ in the film-substrate interface if we know the substrate’s material and the real $k_e$ value that can be obtained from the experimental thermal profiles as we will discuss later.

3. Experimental

For experimentation, gold thin films were deposited on glass substrates by thermal evaporation with different film thicknesses. Corning glass substrates ($5 \times 25 \text{mm}^2$) support the evaporated film with similar area. During growth, the film thickness was monitored with a quartz crystal sensor and a Maxtek TM-400 controller, and verified with a profilometer Dektak 8 after growth. For electrical current application, two AWG-36 cooper wire electrodes were glued onto the gold film ends with conductive silver paint. For thermal measurements, the formed bimaterial system is vertically located in a homemade sample holder (Fig. 2) such that only two contact points avoid the loss of the applied energy by conduction. Two small-mass Omega thermocouples are fixed to measure the temperature on the film and on the substrate’s opposite surface; meanwhile a third thermocouple measures the room temperature variations. The whole system is located on a closed space such that room temperature variations do not affect the heating process. An electrical current is applied to the film through the electrodes with a HP 6643A power supply for heating. The thermal profile, i.e., the heating process with time, is monitored in real time by means of a home-made software developed in LabView 7.0 for visualization. Obtained data are saved as .dat files for further analysis.

![Fig. 2. Experimental setup used for thermal profile measurement.](image-url)
Experimental thermal profiles are compared with the theoretical thermal profiles obtained from the bimaterial model which involves physical properties and the geometrical aspects of the bimaterial system. From the heating profiles, we determine the \( R_{tc} \) value as we will see later.

4. Results

A typical thermal profile obtained with our experimental method is shown in Fig. 3. Three thermal profiles were captured simultaneously (film, substrate, and RT) from the Au/glass (0.5\( \mu \)m/1 mm) bimaterial system during heating [Fig. 3(a)]. First 60 s indicate the thermal stabilization time of the system. After that, a constant electrical current \( I \) is suddenly applied, measuring the corresponding voltage \( V \) in order to calculate the applied total energy \( Q_0 = VI \). As a consequence of the current application, the system increases its temperature with time until stabilization. A small difference \( X(t) \) on temperature between the film and the substrate is found, the film temperature being higher than the substrate temperature. Changes on the RT are used for thermal profile corrections in order to compare with the theoretical simulations in the discussed model. Figure 3(b) shows this behavior showing a temperature difference of about 0.5 \( ^\circ\)C for the Au/glass system analyzed. The difference in temperature \( X \) will depend on the physical properties and the geometrical dimensions of the film and the substrate, the \( R_{tc} \) value, and the applied energy to the film.

4.1. RTC

From the electrical data obtained for different electrical currents applied in different Au film thicknesses, we determine the electrical resistance \( R \) as a function of the change of film temperature \( X_1 \). Thus, the relation \( R = R_0 + R_0 \alpha_r X_1 \) is used for the RTC \( \alpha_r \) determination, by means of the slope measured from the \( R \) versus \( X_1 \) plot. \( R_0 \) is the resistance value at RT. Figure 4(a) shows the measured thermal profiles and their corresponding theoretical values adjusted with the convective coefficient \( h \) and the substrate thermal conductivity \( k_2 \). A simulated heating curve for the film is also shown for comparison.

From the bimaterial model, for an applied constant energy on the film, the thermal profile increases (decreases) its temperature at steady conditions if \( h \) decreases (increases). In a similar way, an increment on the substrate mass \( m_2 \) tends to decrease the slope of heating (i.e., the thermal inertia increases). However, decreasing the \( k_2 \) parameter produces a minor temperature on the surface substrate and consequently a major gradient between the film and the substrate. These three variables \((h, m_2, \text{ and } k_2)\) are used to adjust the theoretical thermal profiles to the measured thermal profiles with high resolution, in order to obtain some thermal properties.

An excellent agreement was found for the Au/glass (0.5\( \mu \)m/1.0 mm) bimaterial system when
0.2 A was applied on a metallic film [Fig. 4(a)]. Similar agreements were found in the thermal profiles for the different electrical currents applied (i.e., different film temperature). Figure 4(b) shows the $R$ versus $T_1$ plot for the same Au/glass system as a result of applying 0.3 A. The slope adjusted value for the RTC calculation gives us $\alpha_{\text{r}} = 0.0034 \pm 0.002$ °C$^{-1}$, showing a good agreement with the value reported in the literature$^6$ for gold. This method was applied on different film thicknesses to determine the corresponding $\alpha_{\text{r}}$ value. In order to have a different way to obtain the thermal profiles, we show in Fig. 4(a) a simulated curve called $X_{\text{film}}$ obtained under similar conditions for comparison. Theoretical, simulated, and experimental thermal profiles for the film are joined and can be seen in the upper curve with high density of points. The simulated thermal profile was obtained by converting the measured electrical resistance value in temperature with the equation $R = R_0 + R_0 \alpha_{\text{r}} X$ and assuming that the $\alpha_{\text{r}}$ value is now known. As can be seen, thermal profiles can be measured, modeled, and simulated, giving similar results.

Figure 5 shows the measurement of different thermal profiles for an Au/glass (0.3 µm/1.0 mm) bimaterial system subjected to different electrical current (0.2–0.5 A) and the corresponding theoretical profiles calculated with the discussed bimaterial thermal model. As can be seen, each thermal profile can be adjusted with a $h$ and $k_e$ parameter in order to match the experimental data. For this case, coefficient $h$ was found to be in the 22.8–28.0 W/m$^2$C range, meanwhile the $k_e$ mean value was estimated about $0.60 \pm 0.05$ W/m°C from measured thermal profiles.

### 4.2. Thermal contact resistance ($R_{\text{tc}}$)

The measured thermal profiles and the adjusted theoretical profiles permit us to estimate the corresponding value of the natural convective coefficient $h$ and the resulting thermal conductivity $k_e$.
For this last case, we will define the effective thermal conductivity \( k_e \) as the thermal conductivity measured as a consequence of the irregular interface junction in the film/substrate system, which can be estimated from the thermal profiles measured on films. Naturally, \( k_e \) values differ from \( k_r \) values, given that heat in the interface is not completely transferred to the substrate by their imperfections. Consequently, \( k_e \) needs to be minor than \( k_r \). In accordance with Eq. (13), the estimated \( k_e \) value helps us to calculate the \( R_{tc} \) value of the film-substrate junction. The \( k_e \) value was calculated from different conditions such that the Au/glass system deposited under similar conditions needs to be similar and independent of the applied energy. By taking the value of the Corning glass as \( k_g = 0.96 \) W/m\( \cdot \)K, it is possible to calculate the \( R_{tc} \) parameter by means of Eq. (13). Substituting the known values we obtain for this case:

\[
R_{tc} = 1 \times 10^{-3} \left( \frac{1}{0.6 \, \text{W/mK}} - \frac{1}{0.96 \, \text{W/mK}} \right) = 6.25 \times 10^{-6} \, \text{m}^2\,\text{W} / \text{K}
\]

The determined \( R_{tc} \) value is close to the reported value of \( 4.2 \times 10^{-6} \, \text{m}^2\,\text{K} / \text{W} \) by MacWaid and Marschall. Electrical properties can also be improved if we take care of the quality of the contact. Chemical reactions and pressure in the interface can improve the contact resistance and the adhesion properties.

In agreement with our results and their comparisons with the values reported in the literature, we can assure that the proposed method based on the thermal profiles is useful for the \( R_{tc} \) determination. Thus, our method is a reliable alternative to estimate the contact resistance for thin film/substrate junctions, by knowing the temperature profile and the physical properties and geometrical aspects of the bimaterial system studied.

### 4.3. Electrical resistivity of films

Another physical parameter that can be estimated from the measured thermal profiles is the electrical resistivity \( \rho \). For that, we will use the relation \( \rho = \rho_0 (1 + \alpha_1 T) \) given that the \( \alpha_1 \) value is known. Different film thicknesses were used to

<table>
<thead>
<tr>
<th>Film thickness (nm)</th>
<th>( Q_0 - V I ) (mW)</th>
<th>( \rho ) (( \mu \Omega \times \text{cm} ))</th>
<th>( \rho_{\text{mean}} ) (( \mu \Omega \times \text{cm} ))</th>
<th>RTC (K/( \Omega ))</th>
<th>( h_{\text{eff}} ) (W/m(^2) K)</th>
<th>( k_e ) (W/mK)</th>
<th>( R_{tc} ) (m/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>47.0 ± 0.7</td>
<td>10.60</td>
<td>0.0027</td>
<td>20.0 ± 0.5</td>
<td>0.35 ± 0.01</td>
<td>1.815 × 10(^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>199.6</td>
<td>118.5 ± 1.6</td>
<td>0.0028</td>
<td>22.2 ± 0.5</td>
<td>0.37 ± 0.01</td>
<td>1.661 × 10(^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>324.4 ± 4.9</td>
<td>12.43</td>
<td>0.0028</td>
<td>25.5 ± 0.5</td>
<td>0.45 ± 0.01</td>
<td>1.950 × 10(^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26 ± 0.2</td>
<td>13.26</td>
<td>0.0028</td>
<td>22.8 ± 0.5</td>
<td>0.60 ± 0.02</td>
<td>6.250 × 10(^{-4})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>57.0 ± 0.6</td>
<td>6.42</td>
<td>0.0028</td>
<td>24.0 ± 0.5</td>
<td>0.60 ± 0.02</td>
<td>6.250 × 10(^{-4})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300.0</td>
<td>103.9 ± 1.9</td>
<td>0.0028</td>
<td>26.0 ± 0.5</td>
<td>0.52 ± 0.02</td>
<td>7.765 × 10(^{-4})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>167.3 ± 1.7</td>
<td>6.54</td>
<td>0.0027</td>
<td>28.0 ± 0.5</td>
<td>0.60 ± 0.02</td>
<td>6.250 × 10(^{-4})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.9 ± 0.2</td>
<td>5.5 ± 0.4</td>
<td>0.0034</td>
<td>23.8 ± 0.5</td>
<td>0.35 ± 0.02</td>
<td>1.815 × 10(^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>47.5 ± 0.4</td>
<td>5.38</td>
<td>0.0034</td>
<td>25.0 ± 0.5</td>
<td>0.34 ± 0.02</td>
<td>1.899 × 10(^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400.4</td>
<td>106.1 ± 0.6</td>
<td>0.0034</td>
<td>27.0 ± 0.5</td>
<td>0.30 ± 0.02</td>
<td>2.392 × 10(^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>137.7 ± 1.0</td>
<td>5.54</td>
<td>0.0034</td>
<td>29.3 ± 0.5</td>
<td>0.38 ± 0.02</td>
<td>1.590 × 10(^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.2 ± 0.1</td>
<td>4.39</td>
<td>0.0032</td>
<td>14.0 ± 0.5</td>
<td>0.55 ± 0.03</td>
<td>7.765 × 10(^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34.7 ± 0.2</td>
<td>4.36</td>
<td>0.0034</td>
<td>15.1 ± 0.5</td>
<td>0.55 ± 0.03</td>
<td>7.765 × 10(^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>501.8</td>
<td>62.8 ± 0.4</td>
<td>0.0034</td>
<td>16.7 ± 0.5</td>
<td>—</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>98.6 ± 0.6</td>
<td>4.32</td>
<td>0.0034</td>
<td>20.0 ± 0.5</td>
<td>—</td>
<td>—</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Physical parameters estimated from the thermal profiles measured for the Au/glass (0.5 \( \mu \text{m}/1.0 \text{mm} \) system for different film thicknesses.

Physical Properties Obtained from Measured Thermal Profiles in the Film/Substrate Bimaterial System
Table 2. Electrical resistivity results measured by the four-probe technique on different regions on an Au/Vi (0.5 µm/1.0 mm) system.

<table>
<thead>
<tr>
<th>Film region</th>
<th>Border thickness (nm)</th>
<th>Voltage (mV)</th>
<th>Electrical current (mA)</th>
<th>$\rho$ (µΩ cm)</th>
<th>$\rho_{mean}$ (µΩ cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>452.4</td>
<td>0.5550</td>
<td>5.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>409.7</td>
<td>0.5710</td>
<td>5.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>439.9</td>
<td>0.6273</td>
<td>6.45</td>
<td>5.33 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>448.4</td>
<td>0.4977</td>
<td>5.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>435.0</td>
<td>0.4877</td>
<td>4.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>452.6</td>
<td>0.4994</td>
<td>5.12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

measure the electrical resistivity for different currents applied. Table 1 shows the different physical parameters estimated from the thermal profiles for different gold film thicknesses. The $\rho$, $\alpha$, $k$, $b$, and $R_{tc}$ parameters are reported.

However, in order to corroborate and compare the previously estimated $\rho$ values, we also measure this parameter on gold films with different thicknesses by the four-probe technique. For that, we used a Jandel sensor head with 1.0 mm as probe separation. We measured $\rho$ in six different parts and we reported a mean value. For that, we used the relationship obtained for thin films $\rho = 4.532(V/I)d_1$.

Thus, we measured the film thickness $d_1$ in each border, where $\rho$ was measured. We used the Dektak 8 profilometer given that quartz sensor gives a global thickness based on the gained mass on the quartz crystal during deposition. Film thicknesses measured with the profilometer are quiet different along the film borders. Table 2 reports the six measurements made on different sites of the gold film and their corresponding electrical resistivity measured by the four-probe technique. The mean value of the electrical resistivity obtained by the four-probe technique was $\rho_{mean} = 5.33 ± 0.9$ µΩ cm, a higher value as compared with the mean value determined from the thermal profiles of $\rho_{mean} = 4.36 ± 0.04$ µΩ cm.

Thus, the uncertainty on the electrical resistivity by the four-probe technique is higher than the value obtained from the thermal profiles. This can be due to the global effect measured in the thermal profiles, instead the local character used in the four-probe technique. By these results, the electrical resistivity values reported from thermal profiles possess better reliability for technological applications by the global effect involved in the measurements.

Figure 6 shows the electrical resistivity behavior measured by the four-probe technique as a function of film thickness for an Au/glass (0.5 µm/1.0 mm) system. A typical decrement of the $\rho$ value with film thickness is observed, tending to the bulk value in the way the Fuchs–Sondheimer and Mayadas–Shatzkes models describe.\

5. Conclusions

We present a thermal model to calculate the thermal profiles in a film/substrate bimaterial system and the experimental setup to measure these profiles in real time with high resolution for different film thicknesses in a Au/glass system. From these thermal profiles, we describe a method to estimate the $R_{tc}$ values of the interface, the RTC, and the electrical resistivity by heating the film...
with different electrical current. From results, we conclude that thermal contact resistance measured for the Au/glass system deposited for thermal evaporation oscillates between $7.7 \times 10^{-4}$ and $1.2 \times 10^{-4} \text{m}^2\text{K/W}$, and increases with film thickness. However, the $R_c$ value would depend on the preparation technique and on the type of interfacial materials, but until now contradictory results have been reported. Micro- and nanoparticles present different behavior with respect to the thermal conductivity and consequently the interfacial thermal resistance. For nanoparticles (nanocolloidal solutions), unusual high $k$ values and $R_c$ values of about $20 \times 10^{-8} \text{m}^2\text{K/W}$ have been reported due to the local convection caused by the Brownian movement. On the other hand, a TiN/steel system deposited by ion plating reported a $R_c$ value of $5 \times 10^{-8} \text{Km}^2/\text{W}$ when measured by a photothermal method (thermal waves).

An Si$_3$N$_4$/SiO$_2$ system deposited by chemical vapor deposition reported a $R_c$ value of $2.25 \times 10^{-6} \text{m}^2\text{K/W}$, similar to the experimental $R_c$ value of $2.05 \times 10^{-6} \text{m}^2\text{K/W}$ reported for the SiO$_2$/Si interface by the same authors. However, Yamane et al. involved in preparing SiO$_2$ thin films with different techniques and measuring them by the $3\omega$ method obtained similar values for the interface reporting a $R_c$ value of about $2 \times 10^{-8} \text{Km}^2/\text{W}$, independent of the growth process and the type of SiO$_2$ thin film.

Finally, electrical resistivity $\rho$ measured on gold films by the classical four-probe technique gives major uncertainty than the estimated value from electrical resistance data obtained from thermal profiles, due to the global character of the measurement, being most reliable. Thus, thermal profiles measured can be useful to determine with high precision some physical properties from a film/substrate system as the bimaterial model combined with a high precision experimental setup demonstrated.

Acknowledgments

This work was supported by CONACyT (México) through project 38480. R. D. Maldonado thanks CONACyT for the scholarship given during his master science studies.

References