A preliminary study of micro heat conduction by hot-tip TPM

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Abstract

Scanning thermal microscopy (SThM) and infrared thermography are widely used for surface thermal characterization. However, the SThM technique is limited to measurement of the non-electrical conductive surfaces and the infrared thermography has insufficient spatial resolution for submicron localized thermal measurement. The “hot tip” Tribological Probe Microscope (TPM) has been designed to achieve better localized thermal analysis function in this paper. The schemes of system design are presented and the principle of the ‘hot-tip’ technique is explained by relating the signals to established thermal properties. After calibrating the lumped thermal resistances (LTR) of the probe and the ambient environment, the LTRs of 5 metal surfaces were measured and compared. In addition, the paper numerically studied the LTR of the indentation interfaces with defined thermal conductivity (TC) by Finite Elment Method (FEM). Numerical linearity was observed and fitted between LTR and TC. Based on the measured LTR and the linearity, the deduced TCs of the 5 metal surfaces are agreed well with the reference values.

Keywords: Micro heat conduction, TPM, lumped thermal resistance, SThM, FEM.

1. Introduction

The failure due to poor heat conduction is an actual problem in the applications of semiconductors. For example, the thermal characteristics of submicron vias strongly impact reliability of multilevel VLSI interconnects because of the self-heating effects. As far as the interconnect components are concerned, the localized thermo-mechanical strength may be interested. As for surface thermal characterization, Scanning thermal microscopy and infrared thermography are widely used in semiconductor industry. However, very rare is the commercial instrument that can combine the localized thermal measurement with the mechanical one.

The need of multifunction instrument for surface measurement is increasing. For example, the topography of a surface can substantially affect the surface properties and the influence has been observed by macroscopic measurements [1]. In other words, there exist the correlations among the surface properties. Though we can measure the surface properties individually by instruments such as Atomic Force Microscope (AFM), Scanning Thermal Microscope (SThM) [2, 3], Nanohardness tester [4], etc., it is still desirable to develop a multifunctional instrument which can measure all the surface properties at the same locations and the mystery of the properties’ correlations could be further unveiled.

In our previous work, a novel multi-functional Tribological Probe Microscope (TPM) [5] was developed to provide mappings of four functions of a surface at micro and nanometer scales. Correlations have been observed among the measured four properties of surface topography, hardness, Young’s modulus and friction. To better understand the micro heat conduction within a simple contact geometry, this paper presents a hot-tip technique that combines the hot-wire method [6] with nanoindentation technique [7]. A new thermal TPM with a hot diamond tip has been developed. Not only overcome the difficulty of SThM on measuring electrical conductive material, the new hot tip has endurable shape and controllable contact geometry, which is essential for localized thermal measurement. This new TPM has a potential of thermo-mechanical characterization by hot-tip nanoindentation at a controlled temperature.

3-059
2.1 Scheme of the TPM-II with hot tip technique

The TPM-II system schematic is shown in Fig. 1. One X-Y stage (AeroTech Inc, ATS40040 and ATS50025) is installed to implement in-plane scanning within the range of 400 × 250 mm² and a theoretical resolution of 10 nm. In vertical (Z) direction, a PZT based positioning transducer (PI NEXLine N214.00) is used to drive the TPM-II probe up and down to provide 20 mm travel range and 5 nm resolution. With a copper crossbeam cantilever as the moving electrode and a fixed electrode plate below, the home-made crossbeam capacitance sensor (2) is designed to act as the contact condition sensor as well as indentation depth sensor (linearity 17.89 nm/mV). A ceramic rod (4) with a Berkovich tip (radius < 200 nm) (6) was attached to the cantilever and a permanent magnet (3) was placed on the top of it. For the hot-tip, a tiny Platinum Wollaston wire (5) was buried underneath the diamond Berkovich tip and a Wheatstone Bridge-based temperature control circuit were developed to fulfill the active thermal measurement with hot-tip technique.

![Diagram of the TPM-II system](image.png)

With voltage-driven current supplying on the biased Wheatstone bridge (R₂+R₃ >> R₁+R₆), the current of Wollaston wire \( I_w \approx I \). As Wollaston wire is thermal-sensitive resistor, the voltage output of the bridge is derived as:

\[
U_{AB} = -I \frac{\alpha R_s R_0 (T - T_0)}{R_i + R_0} = -I \frac{\alpha R_s R_0 \Delta T}{R_i + R_0}
\]

Where the bridge is designed to balance at \( T_0 \) and \( R_3/R_2=R_0/R_1 \). \( \alpha \) is the thermo-resistance coefficient of the Wollaston wire. The PID circuit controls the \( U_{AB} \) stay constantly at zero and therefore the probe temperature, at the steady state, stays unchanged at designed value of \( T_0 \).

2.2 Hot-tip technique for localized thermal conductivity measurement

With the proposed hot-tip technique, TPM-II now is capable of localized thermal conductivity measurement in Constant Temperature (CT) mode with the feedback control of heat power. As shown in Fig.1 (b), the PID temperature control system on the Wollaston wire can be regarded as a thermal source with constant temperature. Basically, the thermal transfer model scheme of the thermal tip both in contact and off contact with sample are shown in Fig.2 (a) and (b). In the figure, \( R_a, R_p, R_s \) represent the LTRs due to air convection, conduction within probe and sample surface, respectively. \( T_w, T_d, T_E \) represent the temperatures of Wollaston wire, diamond surface and environment, respectively. \( C_p \) and \( C_s \) are the lumped effective heat capacity of the probe and heated zone in sample, their effects can be neglected in the steady-state heat transfer network. \( q_1 \) and \( q_2 \) are the total heat flux flow by the network at off-contact and in-contact states.
As the contact area is far smaller than the tip surface, it is reasonable to assume that $R_a$ and $R_p$ do not change between the two states. Let $T = T_w - T_E$, $R_a = cR_p$, then during off-contact and in-contact states, we can get two equations as follows:

$$
\begin{align*}
T &= R_p q_2 + q_2 \left( \frac{R_s}{R_p + R_s} \right) = R_p q_2 + \frac{c q_2 R_s R_p}{R_s + c R_p} \\
T &= R_p q_1 + R_a q_1 = (1 + c) R_p q_1
\end{align*}
$$

When $\Delta q = q_2 - q_1$, we can get the solution

$$
R_p = \frac{T}{(1 + c) q_1}, \quad R_s = \frac{c q_1 - \Delta q}{(1 + c) \Delta q \cdot q_1}
$$

Combine the above solutions, we get

$$
R_s = \frac{c R_p}{1 + c} \left( \frac{c q_1 - \Delta q}{\Delta q \cdot q_1} - 1 \right)
$$

Since the temperature of the Wollaston wire is controlled by PID circuit at constant value, the power supply variation from off-contact state to in-contact can be formulated as follows

$$
\Delta P = P_2 - P_1 = I^2_s R_s - I^2_s R_s = q_2 - q_1 = \Delta q
$$

Where the notation 1, 2 represents the state of off-contact and contact, respectively.

Since the $R_p$, $c$ can be derived in the thermal calibration experiment, the LTR of the sample surface can be further deduced by measuring the variation of power supply $\Delta q$ and the initial power consumption $q_1$.

Assuming perfect contact between tip and sample and neglect radiation effect, the LTR of sample is a function of the sample TC and contact geometry. Theoretically, many models have been developed to analytically characterize this function [8]. In this paper, the thick film model is more suitable since the indentation depth is much less than the sample thickness. The function can be summarized as follows,

$$
R_s = R_{cond} = f(K, L, A) = \frac{L}{K A}
$$

where $L$ is the effective thickness of the thermal layer model, $A$ is the real contact area of heated region. $K$ is the TC of sample. $L$, $A$ are related to the indentation geometries. With controlled certain contact geometry, it is desirable to numerically study the linearity between $1/R_s$ and $K$ by simulating the thermal conduction between the tip and the sample material of known conductivity. Thereafter the corresponding experimental TC could be reversibly deduced from the measured $R_s$. Actually, the lumped surface $R_s$ is partially related to bulk conductivity $K$ due to the existence of air convection or contact resistance. However, it helps to study the micro heat conduction by a further comparison between measured $K$ and the reference $K$ values.
3. Experimentation

3.1 Measurement on thermal resistance of the hot tip and the air convection

![Fig. 3. Linear correlation between temperatures of the Wollaston wire and the Diamond Berkovich tip surface.](image1)

![Fig. 4. Measurement on the lumped thermal resistance of the probe.](image2)

In Fig. 3, the supplied current $I$ was manually adjusted at several values from 10mA to 60mA. According to the equation (1), the Wollaston wire temperature can be calculated by monitoring the bridge output and the supplied current. Simultaneously, the infrared camera Thermal Vision™ A20-V (ThermalCAM™ researcher2.8) was used for the temperature measurement of the tip surface. Figure 3 shows a linearity of 0.5492 between the two measured temperatures. Based on the scheme in Fig. 2 (a), the ratio $c = 0.5492/(1-0.5492) = 1.2183$. In Fig. 4, the curve shows the relation between the temperature variation of Wollaston wire and the power consumed by the heater. Accordingly, the total LTR in Fig. 2 (a) $R_p + R_c = (1+c)R_p = 554.36$ K/W. Therefore, with known $c$, $R_p = 249.9$ K/W.

3.2 Lumped thermal resistance measurement on 5 metals

![Fig. 5. Heat power variation of Wollaston wire after indentation.](image3)

![Fig. 6. Theoretical linearity between sample bulk thermal conductivity and thermal flux through indentation interface simulated by FEM.](image4)

Shown in Fig. 5, the heat power of Wollaston wire was raised abruptly at the beginning of the contact and reached a stable value later. Five metal samples were tested: Copper (Red Brass UNS C23000); Stainless Steel (AISI 4130); Lead, Brass (Yellow Brass UNS C27000) and Aluminium (1210 Alloy). The temperature of Wollaston wire $T_w$ was maintained at 65 °C during the test, while the room temperature was 25.2 °C. The initial heat power $q_1$ was set at 0.011064 W. In each test, the indentation depth was controlled at 200 nm. Table 1 shows the heat power variations of Wollaston wire for the TC measurements. Since the initial
heat power $q_1=0.011064$ W, and $R_p=249.9$ K/W, $c=1.2183$, the LTRs of the 5 metals were calculated according to the eq. (4).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Heat Power variation $\Delta q$ μW</th>
<th>Lumped Thermal Resistance $R_s$ (K/μW)</th>
<th>Lumped Thermal Conductance $1/R_s$ (μW/K)</th>
<th>Deduced Thermal Conductivity K by FEM</th>
<th>Ref. Bulk K value* (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium (Alloy)</td>
<td>109.7617</td>
<td>0.016717</td>
<td>59.820</td>
<td>129.07</td>
<td>151.0</td>
</tr>
<tr>
<td>Copper (Red Brass)</td>
<td>107.1132</td>
<td>0.017134</td>
<td>58.364</td>
<td>125.93</td>
<td>159.0</td>
</tr>
<tr>
<td>Lead</td>
<td>104.9126</td>
<td>0.017496</td>
<td>57.156</td>
<td>123.35</td>
<td>35.0</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>129.4091</td>
<td>0.014158</td>
<td>70.6311</td>
<td>152.40</td>
<td>42.7</td>
</tr>
<tr>
<td>Brass</td>
<td>77.2109</td>
<td>0.023823</td>
<td>41.976</td>
<td>90.57</td>
<td>116.0</td>
</tr>
</tbody>
</table>

* data cited from www.matweb.com

3.3 FE simulation on linearity between $R_s$ and $K$

Finite Element (FE) is widely used in thermal analysis with complex geometry. The aim here is to numerically get the relationship between $R_s$ and $K$. According to the condition of the above tests, a temperature boundary was set on the indentation surface at $T_d$ and sink temperature was set at $T_0=25.2$ °C. The air convection film coefficient was set at 25W/m²K. With defined surface TC and the above boundary conditions, the flux $Q$ through the contact interface was solved and therefore the LTR was derived according to $R_s=(T_d-T_0)/Q$. Figure 6 shows the simulation results of the linearity between the defined surface TCs and the LTRs of the Berkovich indentation interface. Based on the linear curve and the fitted coefficients, the TCs of the 5 metals were deduced from the measured LTRs. The deduced TCs are compared with the reference bulk TCs in the last two rows in Table 1.

4. Discussion and conclusion

As for the metals of high TC, such as copper, aluminium, the measured values agree well with the reference values of their bulk materials but a bit lower because the contact resistances were neglected. However, the deduced TCs of lead and stainless steel are much larger than the reference values. This is because the air convection overwhelms on the micro conduction of the low TC sample. Since all the samples are alloys, grain size effect might be serious, a further calibration test on certain single crystal material is considered. Furthermore, the thermal response performance could be improved by reducing the heat capacity of the probe.

References