1. Introduction

Heat transfer physics at nanoscale have been of great interest in last few decades because of the rapid development of nanotechnology and the miniaturization of sensors and electronic devices [1–4]. Heat transfer is confined in a small area so that heat power is significant and local temperature may be raised at a critical level of device applications, ranging from micrometers to a few tens of nanometers, which affects the reliability and efficiency of the devices [3, 5]. To overcome these undesired heat problems, a good knowledge of heat distribution and more particularly localized hot points in devices and their management is needed. Unlike the optical techniques which suffer the diffraction limit, scanning thermal microscopy (SThM) has enabled us to study heat transfer physics at a very small scale [6–8]. The SThM is based on scanning probe microscopy made of thermal probes which simultaneously provide topographic imaging and thermal information. Using specific probes, the SThM may provide a very high spatial resolution and thermal sensitivity analysis [9]. Analysis of the heat transfer by using SThM is a very active field of research to improve the heat measurement technique [10]. For example, we can refer to QUANTIHEAT [11], the European Union’s research project, where 20 research groups are involved in making the SThM an effective nano thermal measurement technique. Moreover, like electrical transport at the interface between two materials [12, 13], the heat transfer through the interface is a fundamental physical process that significantly controls the effective thermal properties of materials at micro/nanoscales [14–16].
an essential role in SThM measurements, because thermal contact resistance may affect thermal signals. Usually, thermal contact resistance is the consequence of the imperfect matching of boundaries (because the probe and sample are often made of dissimilar materials) and an eventual third body, such as water meniscus, oxide layer and moisture, etc [17, 18]. In general, heat transfer is restricted to highly localized probe/sample contact areas.

In addition, owing to the roughness nature of the probe and sample, nano-size cavities can be induced at the contact area. In those cavities, air can be confined, which may affect the effective thermal contact resistance like water meniscus [19]. Therefore, in a nano-size contact, the impact of the air confinement effect on the heat transfer mechanism cannot be neglected. There has been intense research on the thermal contact resistance at nanoscale but this was mainly performed at a fixed pressure [10, 20, 21]. The contact resistance between the interface of the thin film and samples are also reported in which a high value of mechanical pressure (~0–50GPa) was applied [21]. But, to the best of our knowledge, there is no quantitative analysis reported on the air pressure effect on the thermal contact resistance of the Wollaston thermal probe-sample interaction. Consequently, theoretical and applied research are still needed to better understand the synergistic role played by thermal contact resistance.

We report herein a detailed investigation of heat transfer between the Wollaston wire thermal probe and sample as a function of ambient air pressure. More specifically, we made use of a SThM for the thermal analysis of two samples, fused silica (SiO₂) and titanium (Ti), with different thermal conductivities, under the pressure controlled chamber. Using the experimental data, an analytical model is suggested to retrieve the thermal contact resistance of the thermal probe-sample system. The obtained results are analyzed as a function of air pressure varied from vacuum (1 Pa) to atmospheric pressure (10⁵ Pa). The pressure dependent thermal contact resistance is also discussed according to existing simple models.

2. Materials and method

There are two bulk samples SiO₂ (99.99% of purity) and Ti (99.99% of purity) obtained from Neyco in the form of a disk shape with a diameter of 10mm and height of 2mm. The thermal conductivities of SiO₂ and Ti are 1.28 W m⁻¹ K⁻¹ and 21.7 W m⁻¹ K⁻¹, respectively. The roughness (Rₐ) of the surface of SiO₂ and Ti were assessed via topography analysis.

The topography of the samples were obtained by a commercial AFM of NT-MDT. The average roughness (Rₐ) of SiO₂ and Ti were 0.56 nm and 4.17 nm, respectively. A homemade set-up for thermal characterization of samples under a vacuum-unit, which is shown in figure 1(a), is used. In this unit, the air pressure was varied from vacuum (1 Pa) to atmospheric pressure (10⁵ Pa) by inletting the air into the vacuum chamber. The thermal probe is at a fixed position but the sample is allowed to move with a vertical resolution of 20nm. Only contact (at a point) measurement is possible in this set-up. To make the probe-sample contact, the sample stage moves up towards the thermal probe. The probe temperature is controlled by a Wheatstone bridge, which is depicted in figure 1(b).

In the experiment, a Wollaston wire thermal probe from Veeco is used for the measurements of heat transfer. The Wollaston wire is made of a silver shell of 75 µm diameter and at the center there is a platinum and rhodium (Pt⁰⁹/Rh¹⁰) alloy core of 5 µm diameter. To make the thermal probe, the silver shell over a length of 200 µm is etched off electrochemically and then the bare Pt⁰⁹/Rh¹⁰ wire is bent in a V-shape with a 15 µm radius of curvature. This Pt⁰⁹/Rh¹⁰ wire is a thermo-resistive element and its temperature coefficient is 0.00165 K⁻¹. The thermal conductivity of the Pt⁰⁹/Rh¹⁰ wire is 38 W m⁻¹ K⁻¹. The apex can be heated electrically by direct current (DC) [22, 23]. In the present work, the DC heating mode was employed to provide the heat source to the thermal probe and the average probe temperature was fixed at 150 °C to avoid any moisture. The room temperature and humidity were maintained roughly at 20 °C and 50% respectively throughout the experiment. The device was placed in a temperature and humidity controlled room with ±1 °C and 2% of uncertainties. The probe temperature was kept at 150 °C, so the effect of the room condition was negligible. To control the whole electronics, there was a lock-in-amplifier (Signal Recovery: Model 7265). This lock-in was also interfaced to software which was controlling the sample stage. We measured the probe output voltage of the thermal probe at out-of-contact (oc) from the sample and in-contact (ic) with the sample by using the lock-in-amplifier.

3. Results and discussion

We recorded the output voltage of the interaction of the thermal probe to samples at four different pressures, 1 Pa, 100 Pa, 5000 Pa and 100000 Pa. Figures 2(a) and (b) display the output voltage versus the probe-sample distance for SiO₂.
and Ti, respectively, whereas two sub-figures on a logarithmic scale are shown in figures 2(a) and (b), respectively. At 1 Pa, it can be observed that the output voltage is unchanged when the probe moves from very far to near the contact point, but there was a sudden drop in the output voltage (figures 2(a) and (b)) when the probe comes into contact with the sample. As the pressure was increased to 100 Pa (figures 2(a) and (b)), there was still a sudden drop in the output voltage at the point of contact and there was no significant influence of convection. But, at 5000 Pa, the probe output voltage decreases very slowly from a far distance around 200 µm, suggesting a significant effect of air convection on the output (figures 2(c) and (d)). At 10^5 Pa, which is approximately atmospheric pressure, there was large influence of the air medium (figures 2(c) and (d)).

Figure 3(a) displays the output voltage difference ($\Delta V$ (mV) = $V_{oc} - V_{ic}$) of the thermal probe when the probe is out-of-contact ($V_{oc}$) and in-contact ($V_{ic}$), whereas the normalized output voltage difference ($\Delta V/V_{oc}$) of the thermal probe is depicted in figure 3(b). Measurements and instrument errors are included in the error bars shown in figures 3(a) and (b). To normalize the voltage difference, the voltage out-of-contact ($V_{oc}$) is used because it is the least affected output voltage. As shown in figures 3(a) and (b), the air pressure increases the voltage difference between out-of-contact and in-contact increases and hence the heat transfer increases.

To gain further insights into the heat transfer mechanism at an effective contact (i.e. solid–solid contact, solid–air contact and solid-water meniscus contact) between the thermal probe and sample, we have assessed the thermal contact resistance within the framework of an approximate analytical model, which is presented herein. Generally, at 150 °C, the water meniscus has disappeared [20, 22] and also the contribution of
thermal radiation on the heat transfer mechanism is neglected in SThM [3, 20]. However, in the previous section, the signature of the normalized output voltage difference between out-of-contact and in-contact was established. As a consequence, to extract the probe-sample thermal contact resistance, we propose an analytical model based on the normalized output voltage difference. In our approach to the experimental setup, the same temperature ($T_0$) of the sample used as a heat sink and the probe base were taken into account, which is shown in figure 4(a). Usually, the SThM output voltage ($V$) is related to an excess temperature ($\Delta T$) raised by the applied power ($Q$) through the thermal network is formed with contribution from the thermal contact resistance and the sample thermal resistance. Therefore, $R_{eq}$ can be expressed as:

$$\frac{1}{R_{eq}} = \frac{1}{R_p} + \frac{1}{R_c + R_s}. \quad (4)$$

However, by using equation (2) and (3), the normalized SThM output voltage difference can be written as below:

$$\frac{V_{oc} - V_{ic}}{V_{oc}} = \frac{\Delta T_{oc} - \Delta T_{ic}}{\Delta T_{oc}} = \frac{R_p - R_{eq}}{R_p}. \quad (5)$$

Inserting the equation (4) into (5), the result leads to:

$$\frac{V_{oc} - V_{ic}}{V_{oc}} = \frac{R_p}{R_p + R_c + R_s}. \quad (6)$$

Even though $R_c$ is considered, another important parameter thermal exchange radius ($b$) should be taken into account in order to achieve the maximum accuracy of heat transfer at the nano and/or micro level [20, 24], because in the SThM experiments, heat transfers from the probe to the sample through the probe-sample contact area depicted in figure 4(a). Thermal exchange radius can play a significant role in the heat transfer mechanism owing to its different values with different thermal conductivity samples [24]. A recent study [24] showed that the $b$ value changes with sample thermal conductivity. In addition, the $b$ value significantly influences the thermal resistance of the sample. More specifically, the tip-to-substrate constriction resistance contributes to the $R_c$ [25]. As a consequence, a circular constriction defined as the tip-to-sample thermal exchange surface is considered to determine the $R_c$. Considering the semi-infinite medium (assumption for bulk samples), the thermal exchange radius is given by [24, 25].

$$R_c = \frac{1}{4k_b b} \quad (7)$$

where $k_b$ is the thermal conductivity of the sample. For the Wollaston probe, the value of $b$ was found to be constant ($b = 2.8 \pm 0.3 \, \mu m$) for samples with thermal conductivity values ($<2 \, W \, m^{-1} \, K^{-1}$) but another constant value ($b = 428 \pm 24 \, nm$) was obtained beyond that thermal conductivity value [24]. Thus, equation (6) can be modified as:

$$\frac{\Delta V}{V_{oc}} = \frac{V_{oc} - V_{ic}}{V_{oc}} = \frac{R_p}{R_p + R_c + R_s}. \quad (8)$$
According to equation (8), knowing the values of \( R_p \) and \( k_s \), it is possible to determine the value of \( R_c \). The experimental data was averaged and the standard deviation of the data was found. Also, other parameters were taken into in order to estimate the uncertainty on the calculated \( R_c \) value. The evaluation of \( R_c \) as a function of pressure is displayed in the figure 5. The estimated \( R_c \) shows the range between \( \sim 1.8 \times 10^7 \text{ K W}^{-1} \) and \( \sim 14.3 \times 10^7 \text{ K W}^{-1} \) for SiO\(_2\) and Ti materials. Gotsmann et al [10] reported a \( R_c \) value of \( \sim 10^7 \text{ K W}^{-1} \) under vacuum, whereas many other works ensure \( R_c \) values with the range between \( \sim 10^4 \text{ K W}^{-1} \) and \( \sim 10^9 \text{ K W}^{-1} \) for different systems [20, 24, 26–28]. The study suggests that our estimated \( R_c \) values lie in the range of the values reported in the literature. Therefore, the obtained \( R_c \) values strongly validates the analytical model which is presented here.

Furthermore, the result reveals that the \( R_c \) systematically increases with decreased air pressure. In 2015, Hohensee et al [21] reported that the metal-diamond interface thermal resistance increases with decreased mechanical pressure (~0–50 GPa). The Wollaston probe-sample contact resistance also exhibits similar behaviour in air pressure. Based on effective contact between the probe and sample, such behaviour of the thermal contact resistance can be interpreted. We suggested that heat transport is not only dependent on solid–solid (probe-sample) contact, but also it is intimately tied to the air confined within asperities, which acts as a heat transfer medium. Figure 6 presents a schematic view of the heat transfer from the probe to the sample through the probe-sample contact area. At high pressure (>10^5 Pa), the heat transfer through air contributes significantly to the thermal contact resistance (see figures 6(a) and (b)). Also, the signature of thermal contact resistance ensures that the heat transfer through the effective contact medium is reduced due to an induced void medium, which is created by elimination of the air pockets under low pressure (see figures 6(c) and (d)). In a sense, heat transfer is somewhat impeded at that pressure, because air molecules (heat carriers) become rare. Therefore, the overall thermal contact resistance increases under low pressure, and mainly heat transfers through solid–solid contact at pressures lower than 10^4 Pa.

Alternatively, the obtained \( R_c \) signature can be explained by using the concept of thermal circuit like an electrical analogue. The effective contact resistance can be presented as \( R_c = R_{\text{air}} + R_{\text{solid-solid}} \), where \( R_{\text{air}} \) and \( R_{\text{solid-solid}} \) are the thermal resistance of air and probe-sample contact, respectively. Although pressure is changed herein, the probe-sample contact space is unchanged. Therefore, \( R_{\text{solid-solid}} \) is considered as...
constant throughout the pressure. Moreover, for a rough estimation of thermal conductivity of air as a function of pressure, the given equation is used [29]:

\[
k_{\text{air}} = k_0 \times \frac{1}{1 + \frac{7.6 \times 10^{-5}}{P}} \text{(W m}^{-1}\text{K}^{-1})
\]

(9)

where \(k_0\), \(T\), \(D\) and \(P\) represent the thermal conductivity of air at room pressure and temperature, the average temperature of the probe-sample system, the length of the cavity induced at the Wollaston probe-sample contact area when the probe is the in-contact mode and the pressure. Generally, cavities can be formed due to the roughness nature of the probe and sample. Usually, the manufacturing process creates a groove type roughness. Since the diameter of the Pt/Rd wire is 5 \(\mu\text{m}\) and it is in a cylindrical shape, it is very hard to get the exact roughness of the probe. However, the atomic force microscope (AFM) image of the Pt/Rd apex indicates that there are random grooves of different widths roughly up to 200 \(\text{nm}\) [30]. So, the sizes of the cavities between the probe and sample can be random. We took an approximate 100 nm size cavity to elucidate the variation of contact resistance with pressure. Moreover, it is difficult to determine the exact number of cavities formed at the probe-sample contact area. Even if we change the probe or measurement location, then maybe the number of cavities or size will be different. But, the signal will be the same for a given probe and sample. The sensitivity of the probe also depends on the sample roughness. If the sample is highly smooth then using the same probe, the measurement signal may be a little less. But due to the roughness of the probe, the cavity is formed at the probe-sample contact area. However, since heat transfers through the nano-contact area, we assume that heat also transfers through the void space (cavity) where air is confined. Having \(T = 423\ \text{K}\) and \(k_0 = 0.0284 \text{W m}^{-1}\text{K}^{-1}\), the thermal conductivity of air is approximated as a function of pressure which is displayed in figure 7. The figure exhibits a decreasing behaviour of the thermal conductivity of air with decreased pressure, which is consistent with those reported in the literature [29, 31]. It means that the resistance increases due to the weak dependence of air at low pressure. Thus, the effective thermal contact resistance \(R_c\) increases with decreased pressure. So, the explanation supports the above behaviour of pressure dependent thermal contact act resistance.

In addition, as shown in figure 5, the thermal contact resistance of SiO\(_2\) and Ti are almost similar at high pressure, which is found to be consistent with the previously reported literature [24]. The result indicates that air strongly dominates the effective thermal contact resistance under high pressure (at 5000 Pa and 10\(^5\) Pa). But under low air pressure conditions, there is a difference between the thermal contact resistance of SiO\(_2\) and Ti. Since air pockets are eliminated at low pressure, the heat transfer takes place only through solid/solid contact, which supports the above explanation. This difference of the thermal contact resistance can be explained by thermal mismatch in thermal conductivity of the probe and sample. The difference of the thermal conductivity \((\Delta k = k_p - k_s;\) where \(k_p\) is the thermal conductivity of the probe and \(k_s\) is the thermal conductivity of the sample\)) between the probe and SiO\(_2\) is greater than the difference of the thermal conductivity between the probe and Ti. Thus, a large thermal mismatch between the probe and SiO\(_2\) results in a large thermal contact resistance compared to the one with a probe and Ti where thermal mismatch is relatively less. To address this issue, we include a calculation of the transmission coefficient of the phonon (\(\alpha\)) and thermal contact conductance \((G)\) between two dissimilar materials using an acoustic mismatch model (AMM) and diffuse mismatch model (DMM), which are highlighted below.

Using the Landauer formalism, the per unit area thermal contact conductance \((G)\) between two materials \(A\) (heat source) and \(B\) (heat sink) is given by the following expression [32]:

\[
G = \frac{1}{4} \sum_j \int_0^{\omega_{j}} D_{A,j}(\omega) \frac{\partial n(\omega,T)}{\partial T} \hbar \omega v_{A,j} \alpha_{A \rightarrow B,j}(\omega) d\omega,
\]

(10)

where \(\omega\) is phonon frequency, \(D\) is phonon density of states, \(n\) is the Bose–Einstein distribution function and \(v\) is phonon velocity. The subscript ‘\(j\)’ is for polarization of the phonon. In the AMM and DMM approach, the phonon transmission coefficients are given by [33, 34]:

\[
\alpha_{\text{AMM,} A \rightarrow B} = \frac{\rho_{A} v_{A} \rho_{B} v_{B}}{\rho_{A} v_{A} + \rho_{B} v_{B}}\]

(11)

\[
\alpha_{\text{DMM,} A \rightarrow B} = \sum_j D_{A,j} v_{A,j} + \sum_j D_{B,j} v_{B,j}.\]

(12)

To estimate the approximate thermal contact conductance at the interface of the Wollaston wire thermal probe and sample, we consider a platinum wire instead of a Pt\(_{90}/\text{Rd}_{10}\) wire. We assume that materials Pt, Ti and SiO\(_2\) are homogeneous and isotropic. The data of Pt, Ti and SiO\(_2\) are taken from the literature [35–37] and the values of all of the required parameters used in the models are listed in table 1.

Using the average sound velocities in the materials, the values of \(\alpha\) and \(G\) are determined, which is listed in table 2. As shown in table 2, the AMM model gives a slightly higher value than the DMM model as it considers the elastic interaction of the phonon. The calculation shows that \(t\) and \(G\) values are
higher for Ti than the SiO2. Also in table 2, the thermal contact resistance per unit area ($R = 1/G$) is shown. These values have the same order (10$^{-5}$) as reported in the literature [34]. The study indicates the heat transport through the Wollaston probe-Ti interface is better than the probe-SiO2 interface. Thus, the result evidences the above explanation. We therefore believe that our results are expected to be useful for an SThM user to optimize experimental conditions during measurements and thermal management in micro/nano electronic devices, which work in a variable air pressure environment.

4. Conclusion

In conclusion, the thermal interaction of the thermal probe with SiO2 and Ti bulk samples has been investigated as a function of air pressure varied from vacuum (1 Pa) to atmospheric pressure (10$^5$ Pa). SThM was employed to measure the difference of output voltages of the thermal probe at out-of-contact and in-contact position. The result reveals that the difference of output voltages decreases with the increasing air pressure. In addition, a simple analytical model has been developed to estimate the thermal contact resistance between the thermal probe and samples by using the normalised output voltage difference. The result exhibits that $R_c$ decreases with increasing air pressure, which suggests an enhancement of the heat transfer at nanoscale. The signature of $R_c$ is attributed to the heat transfer through solid–solid (probe-sample) contact and confined air in the nano-size contact. As the amount of air increases, it fills the voids at the interface of the thermal probe and sample. Denser air has greater thermal conductivity and hence lesser thermal contact resistance between the thermal probe and bulk samples. Our finding also exhibits that the heat transfer through confined air is significant at atmospheric pressure, whereas only the solid–solid contact contributes to $R_c$ in a vacuum. The explanation is also supported in the context of the thermal mismatch behaviour, which is studied by using an acoustic mismatch model and diffuse mismatch model.

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