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Short note

Measurement of out-of-plane thermal conductivity of substrates for flexible electronics and displays

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ABSTRACT

Thin, compliant substrates are increasingly being used for flexible electronics, displays, wearable devices, etc. The dissipation of heat generated in such devices is likely to be an important technological challenge that has not been investigated sufficiently. This paper reports measurement of the out-of-plane thermal conductivity of materials for thin substrates, which is a key material property that governs thermal performance. One-dimensional, steady state thermal conduction is set up in the substrate of interest. Measurements of temperature gradient induced by an imposed heat flux result in the determination of out-of-plane thermal conductivity. Thermal contact resistance between the substrate and experimental setup is also obtained. Measurements are carried out on polyethylene naphthalate (PEN) and polyethylene teraphthalate (PET) substrates of varying thicknesses. Based on the measured thermal conductivity, simulations are carried out to compare the thermal performance of a thin substrate with a traditional substrate. Though flexible electronic devices dissipate very less power, the low thermal conductivity measured here, and the low substrate thickness indicate the critical need for thermal management of such devices. Results reported here indicate an upper limit on power dissipation in a flexible device compared to a traditional device for maintaining similar thermal performance. Measurements reported in this paper may help in the fundamental understanding of thermal transport and thermal management strategies in flexible electronics and displays.

1. Introduction

While traditional microelectronic devices are manufactured on thick, hard substrates, there has been a lot of recent interest in thin substrates, with applications including flexible displays [1,2], wearable electronics [3,4], electronic textiles [4], sensors skins [5,6], and thin-film transistors (TFTs) [7–11]. Substrate thickness for such devices can be as low as 25 μm [1]. As these technologies evolve, there will be a need to evaluate the thermal management of these devices. Even though such devices typically generate very less power compared to traditional electronic devices, there are likely to be several thermal management concerns. The dramatically reduced substrate thickness hinders heat spreading. Non-traditional substrates such as plastics introduce additional thermal concerns, such as low thermal conductivity [1,2], excessive thermal expansion, and low glass transition temperature [12]. The unavailability of traditional thermal management tools such as heat sinks and heat pipes may further exacerbate the challenge of thermal management in such applications. As the complexity and power consumption of flexible devices is expected to increase in the future [13,14], it is critical to understand the nature of thermal transport in these substrate materials and establish power limits to ensure device reliability.

Thermal conductivity is a key material property that determines the thermal performance of devices and substrates [15]. In general, thermal conductivity may be anisotropic, depending, for example, on grain orientation for crystalline materials [16]. In the case of substrates for electronic devices, the out of plane thermal conductivity may be more critical, since it directly affects thermal conduction from the device to the substrate backside, from where it may be dissipated into the ambient. A number of experimental techniques exist for thermal conductivity measurements on electronic materials [15–18]. These methods are usually based on steady-state, transient or periodic heating of the test material, and measurement of subsequent temperature rise at one or multiple locations [15–18]. Both electrical and optical methods for heating and temperature detection have been investigated [15]. Within electrical methods, both DC and AC-based methods have been used [19–23]. Separate methods have addressed either relatively thick substrates (hundreds of μm or thicker) [22], or thin films (a few μm or thinner) deposited on a thick substrate [21,23]. Sinusoidal heating of a thick substrate with a thermal penetration depth smaller than substrate thickness has been used widely [22]. Thermal conductivity of thin films has been measured based on the difference in thermal response of a thick substrate with and without the thin film [21]. Thermal conductivity of free-standing thin films has also been measured [18]. However,

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there is a lack of experimental measurements on thin substrates in the thickness range of a few tens of μm, for which methods for neither thick substrates nor thin films are appropriate. For example, the use of 3-ω method [22] for this thickness range would require unrealistically large heating frequencies. While bulk-form thermal conductivity has been measured in the past for materials commonly used for thin substrates such as polyethylene naphthalate (PEN) and polyethylene teraphthalate (PET), an in situ measurement on substrates of the thickness of interest to flexible devices – a few tens of μm – is desirable, since thermal conductivity is known to depend strongly on processing conditions [15].

In this paper, one-dimensional steady-state thermal conduction is set up in a substrate of interest for measurement of out-of-plane thermal conductivity of the substrate. Temperature and heat flux measurements are used to determine total thermal resistance of the substrate. Measurements on multiple substrates of the same material but different thicknesses result in determination of thermal conductivity of the substrate.

The next section describes the experimental setup. Data analysis and results are presented next, followed by a discussion on the implications of the measured thermal conductivity on thermal management of flexible electronic devices.

2. Experiments

Fig. 1 shows an image and a schematic of the experimental setup. The setup utilizes two identical copper blocks. The substrate of interest is sandwiched between the two blocks. The two faces of copper blocks that come in contact with the substrate are polished in a two-step process, using a 120 grit sandpaper belt on a LECO BG-30 polisher, followed by a 1200 grit sandpaper drenched with 0.05 μm alumina microparticles on LECO VP-150 polisher. A thin Kapton heater of the same size as the block cross-section is attached to the face opposite to the polished surface of one of the blocks. A through-hole is drilled close to the face opposite to the polished surface of the other block. This through-hole is connected to flexible tubing carrying cooling water from a chiller. Seven holes of 1.0 mm diameter extending to the center of the block are drilled along the length of each block. The holes are spaced closer to each other near the polished surfaces. T-type thermocouples are inserted all the way into the holes to measure the block temperature as a function of distance in each block. Holes are drilled along expected isotherms in order to minimize heat loss down the thermocouple wires. Based on the thermocouple wire dimensions and material, and the maximum temperature reached during experiments, the worst-case heat loss due to thermal conduction down the thermocouple wires is estimated to be only 0.2% of the applied heat. Omega CC High Temperature cement is used to fix thermocouples in place and provide good thermal contact with the copper block. All faces of the copper blocks except the polished faces are then insulated with fiberglass insulation tape. The Kapton heater attached to the top block is electrically heated using a power source. A Keithley 2100 digital multimeter is used to monitor voltage across the heater. Electrical resistance of the heater is found to remain nearly constant within the temperature range of this experiment. Thus, the heater provides a constant heat flux through the experiment.

Temperature measurements are recorded with 1 Hz frequency through a National Instruments 9213 DAQ and LabView software. Fig. 2 plots the measured temperature at steady-state as a function of distance away from the heater end for PEN substrates of different thicknesses. In each case, the temperature profiles in the top and bottom heater are both linear, with nearly the same slope. This indicates linear, one-dimensional heat flow in the experiment. The offset between the two lines when extrapolated to the interface location determines the temperature difference across the two heater blocks. Figure S.1 in Supplementary Information plots the temperature difference as a function of time after initiation of heating for five different substrate thicknesses. This plot shows that temperature difference across the blocks increases with time, and eventually reaches steady state, at which time all heat generated in the heater conducts through the copper blocks, and no heat is stored within. Steady state is reached in these experiments typically within 1300 s.

3. Results and discussion

At steady state, the total thermal resistance across the copper blocks, R_{total} is obtained from

$$R_{total} = \frac{\Delta T}{Q} \tag{1}$$

where ΔT is the steady state temperature difference across the interface and Q is the heat flux. Q can be obtained from Fourier's law using the measured temperature slope dT / dx in the two copper blocks.

Note that R_{total} includes contributions from material thermal resistance in the substrate, R_{subs} and thermal contact resistance at the interface between copper and substrate, $R_{Cu\text{-}subs}$. The relative proportion of these

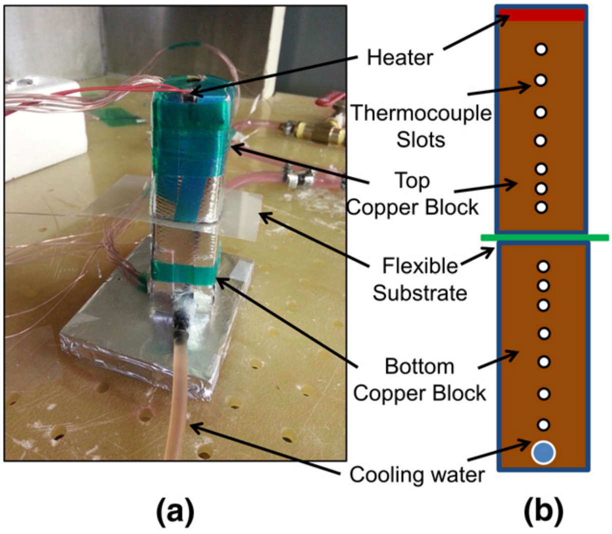

Fig. 1. (a) Image, and (b) schematic of the experimental measurement setup for out of plane thermal conductivity measurement of a flexible substrate.

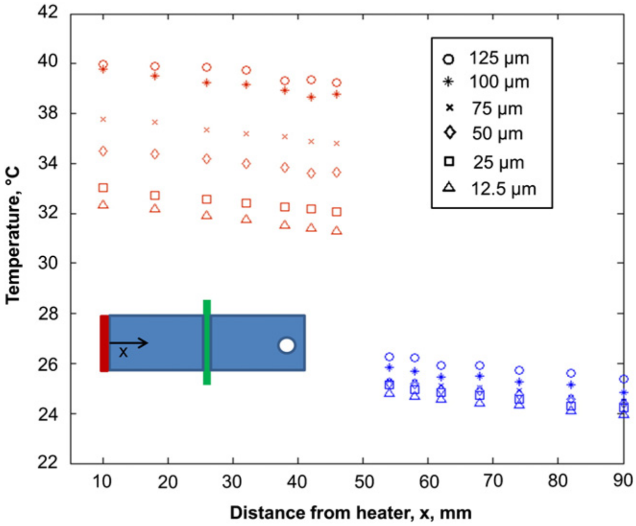

Fig. 2. Measured temperature as a function of distance away from heater for 25 μm PEN substrate.