Experimental Study of Heat Transfer in Micro Glass Tubes Mediated by Surface Phonon Polaritons

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Abstract. We report a temperature measurement of the surface of micro structured glass tube, affected by surface phonon polaritons’ (SPPs) energy enhancement. The glass tubes were designed to guide monochromatic thermal energy to improve heat conduction or serve as radiative source. The simulation results show strong enhancement of the Free Path when a waveguide radius is between 2.0 and 10 µm. Absorption of enhanced SPPs energy on the waveguide areas with high absorptivity has some possibility to cause local rise in temperature. Various shapes of micro glass tubes are simply fabricated, and heated by using a Pt wire in a vacuum chamber. Surface temperatures of glass tubes are measured by infrared digital thermal microscope as well as by using a micro-thermocouple to investigate the temperature distribution on both tapered and thin micro glass tubes.

1. Introduction

Heat conduction in small dimensional systems is evidently affected when the system size shrinks to dimensions comparable to the phonons or the electrons mean free paths or the wavelengths of those heat carriers. Consequently, fields such as thermoelectricity and microsystems thermal management have been deeply metamorphosed by progresses in small-scale heat transfer. Increasing in thermal conductivity is of interest in optoelectronics and microprocessors where heat dissipation is becoming one of the limiting factors in performance. The ability of a material to conduct heat is phenomenologically described by its macroscopic thermal conductivity. In amorphous materials this thermal conductivity is generally low, with no established methods to increase the capability for heat conduction.

A recent theoretical work [1] has, however, proposed an original approach capable of enhancing the effective thermal conductivity of polar thin films. Predictions show that glass thermal conductivity is enhanced by a factor of three in films with 40 nm thick at 500K. This is realized by exploiting the energy flux transported by Surface Phonon Polaritons (SPPs). SPPs are surface waves produced by the coupling of atomic vibrations with the electromagnetic field [2-4]. That is hybrid waves of optical phonon mode and electromagnetic wave, which satisfies special boundary conditions therefore called

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Surface Phonon Polaritons (SPPs). The SPPs transverse magnetic mode spectrum is between transverse optic mode and longitudinal optic phonon frequencies [5]. When calculating surface phonon polaritons, a plane wave description is usually implemented with the following phase term:

$$\exp\left\{ i \left( kx - \varepsilon(\omega) \frac{\omega^2}{c^2} \right) \right\}$$

where $k$ is the complex wave vector of SPPs, $\varepsilon$ is dielectric constant and $\omega$ is the angular frequency. In general, phonon frequencies of lattice waves lie in the infrared and the coupling with long wavelength will thus take place in this region [4]. The electromagnetic flux which propagates waveguide decays exponentially, and those waves are strongly enhanced when they couple between themselves. Because they are monochromatic waves in the infrared (IR) [6], SPPs might be able to provide monochromatic sources just based on simple heating. At ambient temperatures, they also might produce abnormal heat conduction phenomena related to ballistic regimes of transport. Considering heat transfer in the propagative direction of SPPs, quite recent works have tried to show heat conduction improvement in nanofilms. However, the coupling is not favoured in this configuration because the film dissipates the electromagnetic energy and the coupling distance is too small. Therefore, SPPs based heat conduction in a glass microtube is here investigated. The glass microtube is a one-dimensional system where all wave-vectors have the propagation direction of the tube axis. The modelling of the tubes consists in solving Maxwell equations and the field continuity relations.

On the other hand, SPPs were first proven to allow for controlling the spatial or the spectral coherence of the surface emission of thermal sources [8]. The increase of the radiative heat transfer between two parallel surfaces and between a dipole and a surface was also investigated [9]. Those works proved that SPPs could enhance heat radiation by several orders of magnitude when the separation distance becomes smaller than the tenth of the wavelength. This is proven by recent measurements of the heat flux between a microsphere and a hot surface [7]. The conductive flux along a nanostructure is also significant because it is well known that SPPs have long propagation lengths, which in turn can lead to large effective thermal conductivities. In addition, in nanostructures, surface effects are more important than volumetric effects due to a high surface area to volume ratio. SPPs may also play an important role in energy transport along films or wires with nanoscale thickness or diameters because the waves on both surfaces can be coupled together.

In this study, we aim to measure temperature of wave-guide glass tubes, with energy transport affected by SPPs enhancement. In order to prove the simulation results by an experiment, micro glass tubes were fabricated by a simple method, i.e. pulling and heating a capillary tube. When the diameter of the tube is of submicron order, SPPs energy will be enhanced. Energy enhancement might cause local temperature rise if a highly absorptive material is deposited. The purpose of this research is to design micro glass tubes in order to measure heat conduction due to SPP contribution.

2. Experimental details

2.1. Fabrication of micro glass tubes

Several shapes of micro glass tubes (borosilicate glass capillary, GD-1, Narishige) guiding SPPs energy were fabricated by using a glass pipette puller (PC-10, Narishige). The shapes of micro glass tubes depend on joule heating power, pulling force as well as of the position of the tube on the puller. Theoretical results show that if the radius of the waveguide is between 2.0 and 10 µm, SPPs’ mean
free path increase leads to heat flux enhancement. As shown in Figure 1, tapered micro glass tubes with different tip angles were successfully controlled and fabricated. To excite the energy of phonon polaritons, elementary excitation (phonon) and electromagnetic waves have to be combined, and atoms in the waveguide have to form dipole in order to generate local electromagnetic waves. Borosilicate glass is a polar dielectric material that can support surface phonon polaritons, even if the resonance is broadened due to the strong damping in amorphous materials [1].

![Fig.1. SEM images of tapered micro glass tubes.](image)

2.2. Carbon coating
It is expected that absorption of enhanced SPPs energy lead to a local temperature increase in high-energy absorption areas. Theoretical results reveal a very strong enhancement of the free path in a narrow range of tube radii between 4.0 and 10 µm. Some apexes of micro glass tubes satisfy this condition. To improve the absorption of SPPs’ heat flux and amplify the effect of SPPs’ coupling along the tube, a 240 nm thick carbon layer was deposited over 150 microns from the tip end. To achieve the enhancement of SPPs’ energy absorption, sputtering of carbon is selectively done by shadow masking on micro glass tubes. To quantitatively show the carbon evaporation, ultimate analysis of glass tube surface with Energy Dispersive X-ray spectroscopy (EDX) was done. Figure 2 shows that the carbon was coated along the narrow part of the glass tube till the end of tip.

2.3. Heating experiment
The experimental set-up for proving abnormal heat conduction consists in sticking a micro glass tube on a DC heating Pt wire on one end and measuring the temperature on the other end by using a deposited thermocouple as well as an infrared thermo microscope (FSV-GX7700, Apiste). Schematic view and photos of the experimental setup are shown in Figure 3. The heat was induced in micro glass tubes by applying a DC voltage to the Pt micro wire. A platinum wire 50 µm in diameter is used as a heat source shown in Figure 3. The glass tubes and the Pt wire area contacted directly. The Pt wire is soldered onto a printed circuit board, and connected to a dc voltage/current generator through copper wire. The DC voltage is applied to the Pt wire and the heating of micro glass tubes was operated in medium vacuum condition (less than 30 Pa). The IR thermo microscope temperature mapping along the micro glass tube consecutive to the heating experiment is shown in Figure 4.

The proper emissivity values of the surface of the glass tube and the carbon layer are needed for a precise investigation of the temperature measurement by using an infrared thermo microscopy. In this paper, the emissivity is estimated by comparison between a contact measurement based on a thermocouple and the infrared signal of the digital thermo microscopy. A K-type thermocouple
(CHAL-0005, Omega Eng. INC, US & Canada), whose apex diameter is about 40 µm, is used for the contact temperature measurement.

As a result, the glass tube emissivity is about 0.70 and the carbon coated one is about 0.45. The
contact temperature measurement of the glass tube apex is very difficult, so the whole glass tube emissivity is approximated to 0.70 and the carbon coated area emissivity is approximated to 0.45, respectively.

Air leak occurs because of the chink between the vacuum chamber and its cover, the rotary pump is therefore kept running during the heating experiments. Metal cover on the vacuum chamber has a transparent CaF$_2$ glass window. The windowpane of the vacuum chamber was made with calcium fluoride, which is transparent in the IR wavelength range; a calibration through the thermo microscopy had to be performed before actual temperature measurements because the CaF$_2$ glass also has its specific absorption spectrum.

Therefore, the measured temperature values through the cover glass are lower than the real values. Calibration was carried out by considering infrared energy absorption and a correction coefficient of 1.4 was calculated in this case. It converts temperature values measured through CaF$_2$ into proper temperature values.

3. Temperature distributions with different micro glass tubes

The temperature profile based on IR microscopy is provided to investigate the SPPs’ contribution in the heat transfer along the tube. Figure 7 (a) shows the temperature profile on tapered micro glass tubes with tip angle of 2.6° during heating by the Pt micro wire. The temperature decreased versus distance from the heating source (Figure 7 (b)). Note, that the heat conduction tended to decrease steeper through the tubes with increasing Pt wire heating. Moreover, the temperature of the Pt micro-heater, which was measured with a thermocouple, was matched to the results measured by IR thermo microscope.
Fig. 7 Temperature profile of tapered micro glass during heating by Pt micro heater (a) IR microscopy temperature mapping, (b) temperature with different applied voltage, (c) Carbon coated area in apex of tube

Temperature distributions on the tapered and thin glass tube, shown in Figure 8 are also reported with different applied voltages. Temperature data of the carbon-coated area of the glass tube is described in blue dots in the lower right of Figure 8. According to the temperature data along the glass tubes as shown in Figure 8, the local thermal resistance, which is directly revealed by the spatial gradient of temperature, was increased steeply in the thin part of the micro glass tubes due to the cross section reduction. This same local resistance reached a very high value in the carbon-coated part due to the drastic diameter reduction providing an adiabatical boundary condition. Thermal conductivity caused by SPPs’ contribution and the corresponding local temperature rise in carbon-coated part could not be obtained at present.

4. Thermal Conductivity of micro glass tubes

To investigate the effects of SPPs and scale effects for thermal conductivity of micro glass tubes, heat conduction equation is solved by finite element method, and the comparisons of heating experimental results and simulation results are done. Thermal conductivity of pyrex glass changes its value depending on the temperature as shown in Figure 9. Temperature dependency of thermal conductivity is considered in the calculation. The comparison of experimental results and simulation results are shown in Figure 10. The maximum error between experimental data and simulation data are seen at the tapered area of the glass tube as shown in Figure 10. Abnormal effects of SPPs against thermal conductivity of glass tubes has not been obtained in this experiments.
5. Conclusions

We successfully fabricated several shapes of micro glass tubes with different tip angles by a simple pulling and heating method. The temperature of tapered micro glass tubes was measured in vacuum conditions by the infrared thermal microscope. Heating was conducted by applying a DC voltage to the Pt micro-wire. When a higher temperature was applied to the tapered glass tubes, the heat was less conducted to the tip of the tubes. Future works will consist in calculating thermal conductivity based
on exact the dimensions of the microtube and an AC current as heat source. The simulation result tends to show that the SPP propagation is improved due to the special waveguide shape. Measurement of the temperature rise at the glass tube apex to confirm of SPP energy transport is the goal of this experiment. However, local temperature rise at the carbon-coated part could not be observed yet. The experiment will be conducted in further studies to analyse the effect of the coated carbon on the thermal conductivity and AC voltage heating will be investigate to extract transport properties with accuracy.

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Acknowledgments
This work was supported by KAKENHI (22360085), Grant-in-Aid for Scientific Research (B) by the Japan Society for the Promotion of Science.