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Micro Thermal Diode with Glass Thermal Insulation Structure Embedded in Vapor Chamber

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Abstract. This paper reports a novel micro thermal diode with an embedded micro glass thermal insulation structure. The diodicity is given by wettability-driven one-way fluid circulation mechanism without any external force. The water circulation only occurs in "forward" mode, resulting in low thermal resistance. The glass thermal insulation structure enhances thermal insulation in "reverse" mode. The thermal insulation in forward and reverse mode, R_f and R_r, were measured as 2.06±0.34 K/W and 3.04±0.38 K/W, respectively. Therefore, the performance index, R_r/R_f, was 1.47±0.14.

1. Introduction

A thermal diode is one of important components of a micro thermal device such as a micro refrigerator and a thermal energy harvester [1]. A thermosyphon, in which one-way working fluid circulation is driven by gravity force, can be used as a thermal diode. However, the heat transfer property strongly depends on the gravity direction. In addition, the gravity force becomes quite small compared with surface tension in a microscale region, which limits the miniaturization of the thermosyphon. Therefore, surface-tension-driven fluid circulation mechanism is more suitable in a micro thermal diode. In this paper, we propose a novel micro thermal diode, in which the one-way working fluid circulation is driven by wettability difference between condensation and evaporation parts and thermal insulation in the reverse direction is realized by an embedded thick glass microstructure.

2. Structure and principle of the micro thermal diode

Figure 1 shows the structure and working mechanism of the micro thermal diode. The device consists of two plates: an outlet-side plate with a superhydrophobic surface and an inlet-side plate with microchannels with a hydrophilic surface. The microchannels are filled with working fluid. A glass microstructure, which is embedded in the inlet-side channel plate, forms a thermal insulation chamber wall.

In forward mode, the inlet-side plate with the microchannels is heated, while the outlet-side plate with the superhydrophobic surface is cooled (Fig. 1 (b)). The working fluid in the microchannels evaporates and condenses on the superhydrophobic surface, which makes small droplets on the surface. The droplet glows by coalescing, and then returns to the microchannel when it touches to the hydrophilic microchannel wall. Thus, the evaporation-condensation cycle continues like a heat pipe. The evaporation rate from microchannels is higher than that of pool boiling [2]. In addition, the heat transfer coefficient of drop-wise condensation is much higher than that of film-wise condensation [3].

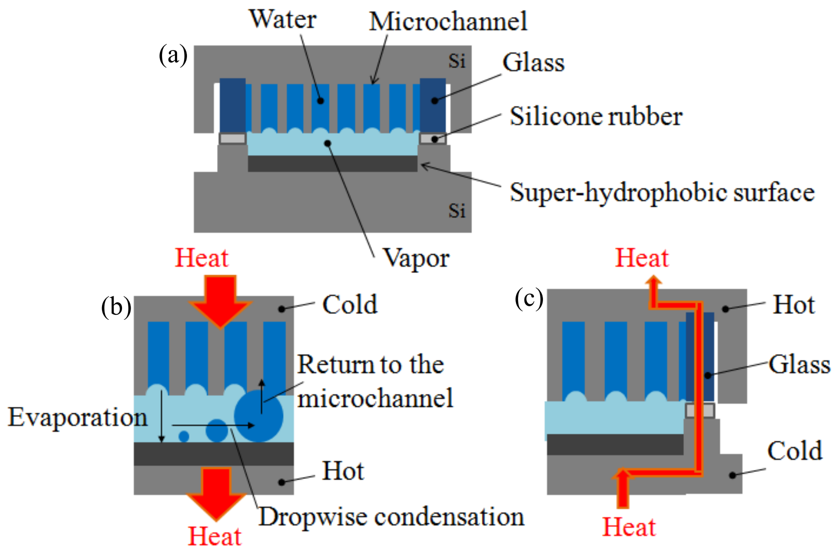

Fig. 1 Structure and working mechanism of the micro thermal diode. (a) Cross sectional schematic of the device. (b) Water circulation mechanism in forward mode and (c) heat flow path in reverse mode.

From these mechanisms, the thermal resistance in forward mode is quite low.

On the contrary, the outlet-side plate with the superhydrophobic surface is heated in reverse mode (Fig. 1 (c)). The working fluid on the superhydrophobic surface evaporates and condensed on the microchannel wall. However, the condensed liquid remains in the microchannels because of their hydrophilicity, and does not return to the heating area [4]. Therefore, the heat mainly flows thorough the chamber wall, which is made of thick glass for high thermal insulation.

3. Device fabrication

Figure 2 shows the fabrication process. First, micromolds for the glass thermal insulation structure were formed on a Si substrate (Fig. 2 (a.1)). A borosilicate glass plate was anodically bonded to it under vacuum condition at an applied voltage of 600 V and a substrate temperature of 400°C (Fig 2 (a.2)). The glass was reflowed at 900°C under atmospheric pressure to fill the vacuum-sealed molds (Fig. 2 (a.3)). The unnecessary glass overlapping the surface was removed by grinding and polishing (Fig. 2 (a.4)), and the microchannels were formed by deep reactive ion etching (Fig. 2 (a.5)). Finally, the surface was covered with SiO_2 to increase the wettability (Fig. 2 (a.6)). Figure 3 shows the fabricated microchannels and the embedded glass thermal insulation structure on the inlet-side plate.

For the outlet-side plate, another Si substrate was etched to form mesa structures, and a thin film of Au/Cr was deposited (Fig. 2 (b.2)). Then, a Ni/PTFE film was electroplated using a solution consisting of 1.2 M of $Ni(NH_2SO_3)$, 0.5 M of H_3BO_3, and 40 g/L of PTFE particles with an average diameter of 220 nm [5]. A pulsed electroplating method was used, where “on” time was fixed at 10 ms and “off” time was varied from 2 ms to 10 ms. The temperature of the solution was kept at 55±1°C, and the current density in “on” period was set at 0.2 mA/dm^2. The film was annealed at 300°C in a vacuum furnace to form a network of PTFE, and Ni was etched by nitric acid to make a porous PTFE surface. Figure 4 shows the superhydrophobic surface made of porous PTFE and a water droplet on it. Figure 5 shows the contact angle of the water droplet on the superhydrophobic surface. The contact angle increased with the etching time due to lotus leaf effect. When the etching time was too long, however, the contact angle again reduced, because the PTFE particles were partially removed. The maximum contact angle obtained was about 160°.

4. Experimental result

4 μL of water was sealed between the two plates with a silicone rubber gasket. Figure 6 shows the experimental setup. The test device was placed between two heat conduction blocks, one of which was

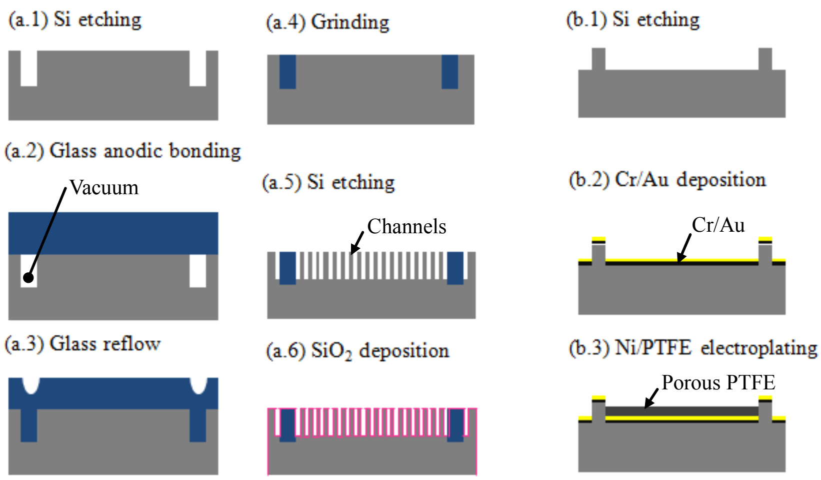

Fig. 2 Fabrication process of (a) the inlet-side plate with microchannels and (b) the outlet-side plate with a superhydrophobic surface.

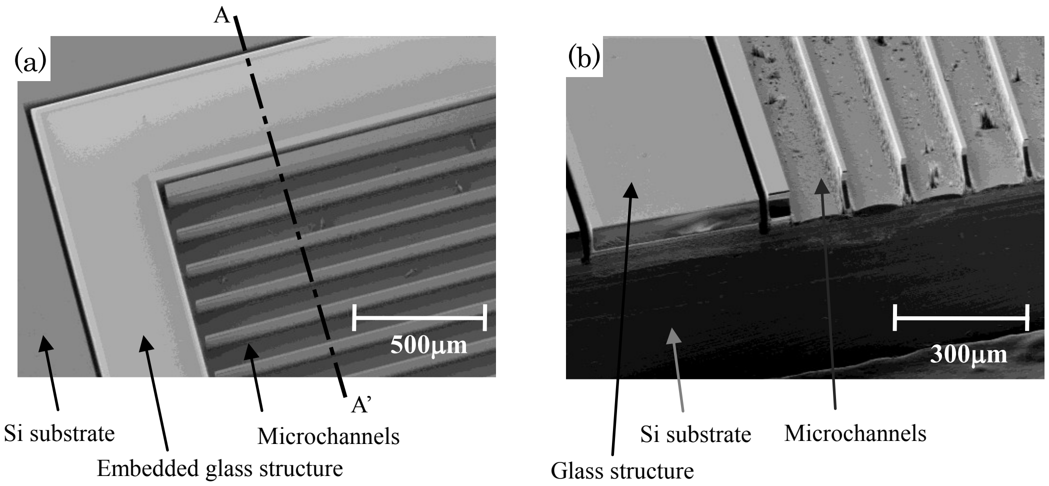

Fig. 3 SEM of the inlet-side plate with microchannels. (a)Top view and (b) A-A' cross sectional view.

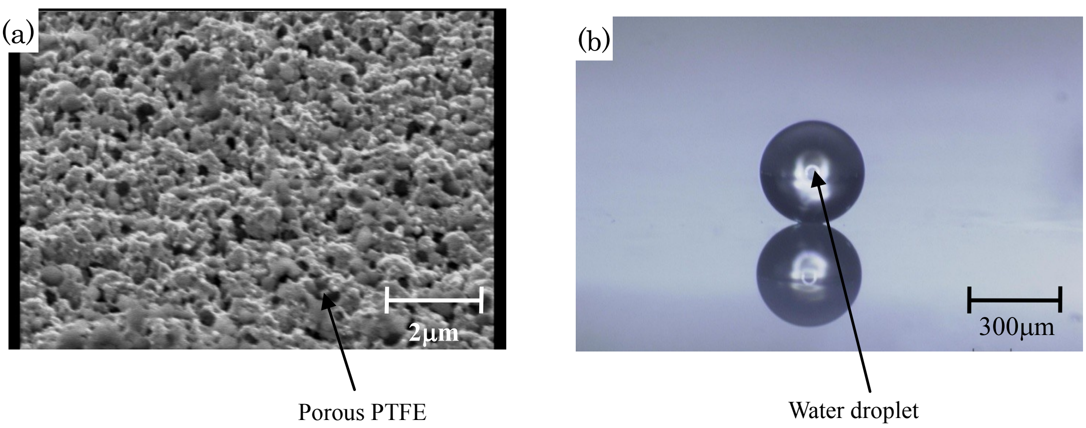

Fig. 4 Superhydrophobic surface. (a) Porous PTFE and (b) a water droplet on it.

heated by an electric heater and the other was connected to a heat sink for cooling. Heat flow through the device, Q, was measured by a heat flux sensor (FMR-200-K, Concept Engineering Gmbh, Germany), and temperature difference across the device, ΔT, was measured by thermocouples attached on both sides of the device. The thermal resistance, R_{th}, was then calculated as

$$R_{th} = \Delta T / Q.$$

The performance index of the thermal diode was defined as

$$R = R_r / R_f,$$

where R_f and R_r are the thermal resistance in forward and reverse mode, respectively.

Figure 7 shows measured thermal resistance in forward and reverse mode. When the heat flow was small, the S/N ratio of the data was low due to small temperature difference across the device. Therefore, we use the experimental results where the heat flow was larger than 1 W for the following discussion. The conductive thermal resistance of the glass wall was measured using the device without water. The measured thermal resistance was about 4.09±0.33 K/W, which is roughly consistent with a theoretically estimated value of 3.0 K/W. The reverse mode thermal resistance was measured as 3.04±0.38 K/W, and thus heat mainly flows through the glass wall in reverse mode. On the other hand, the forward mode thermal resistance was about 2.06±0.34 K/W, which was much smaller than that of reverse mode. This result suggests that water droplets returned to the microchannels against the gravity as intended. The performance index, R_r/R_f, was 1.47±0.14.

5. Conclusion

We designed and fabricated a micro thermal diode with a glass thermal insulation structure embedded in a vapor chamber. The fabrication processes of the glass micro structure and the porous PTFE superhydrophobic surface were developed. The thermal resistances in both forward and reverse mode were measured. The result confirmed the flow direction dependency of the thermal resistance, and suggested that the water circulation mechanism worked against the gravity as intended. The performance index, R_r/R_f, was as high as about 1.47±0.14.

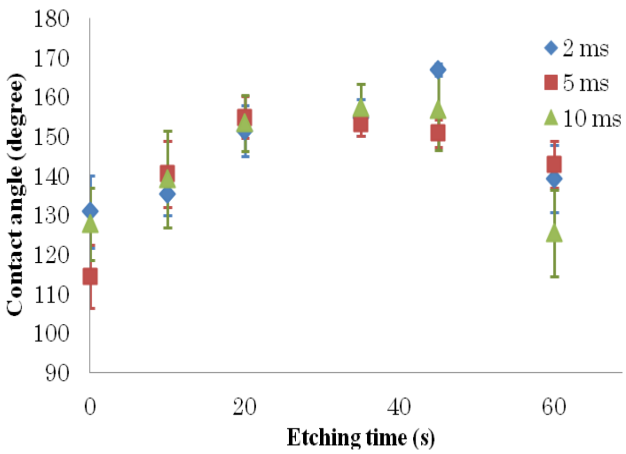

Fig. 5 Contact angle of water on the superhydrophobic surface with respect to etching time. Different conditions of "off" time in the pulsed electroplating exhibited similar results.

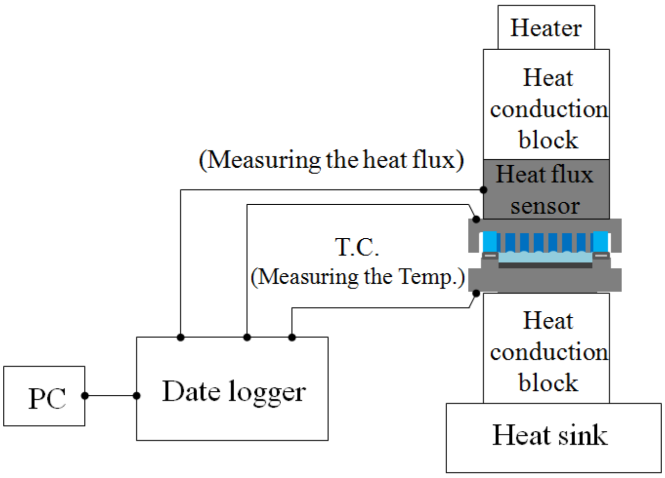

Fig. 6 Experimental setup to measure thermal resistance.

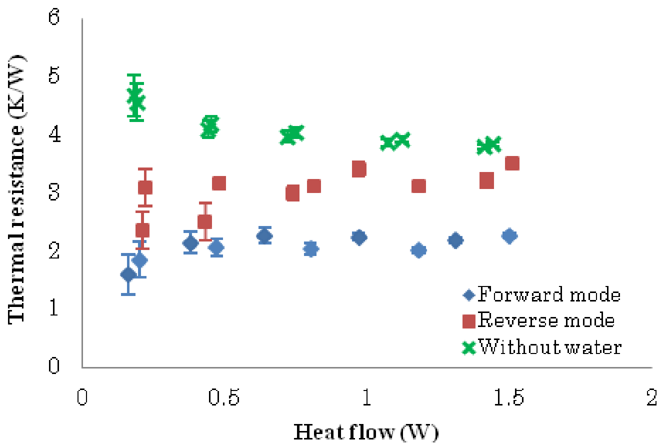

Fig. 7 Measured thermal resistance in forward and reverse mode compared with that without water.

6. Reference

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