Micro thermal diode with glass thermal insulation structure embedded in a vapor chamber

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Received 19 November 2016, revised 30 January 2017
Accepted for publication 6 February 2017
Published 21 February 2017

Abstract
This paper reports a micro thermal diode based on one-way working fluid circulation driven by surface tension force. In forward mode, working fluid evaporates and condenses at a heated and cooled area, respectively, and the condensed liquid returns to the evaporation area due to the wettability difference. By this vapor-liquid phase change mechanism, the overall heat transfer coefficient becomes high. On the other hand, in reverse mode, no continuous evaporation-condensation cycle exists. The conductive heat loss in reverse mode was minimized by an embedded glass thermal isolation structure, which makes overall heat transfer coefficient low. The test device was made by a standard MEMS process combined with glass reflow and gold bump sealing. The overall heat transfer coefficients of 13 300 W m⁻² K⁻¹ for forward mode and 4790 W m⁻² K⁻¹ for reverse mode were measured. The performance index of the micro thermal diode was about 2.8.

Keywords: thermal diode, embedded glass structure, surface tension driven droplet actuation

(Some figures may appear in colour only in the online journal)
surface-tension-driven fluid circulation mechanism is preferable for the micro thermal diode.

Recently, a thermal diode, in which the working fluid was driven by using a droplet jumping phenomenon on a super-hydrophobic surface, was proposed and large diodicity was reported [8]. However, the test device proposed in it was fabricated by a standard machining, i.e. the working fluid was encapsulated by using a gasket and mechanical clumping mechanism, which limits the miniaturization and small gas leakage through the gasket introduces non-condensable gas (N₂ or O₂) into the chamber resulting in a short lifetime of the device. In addition, super-hydrophobic surface was mandatory to jump the condensed droplet, which requires precise control of surface quality and the super-hydrophobicity should be kept for a long time.

In this paper, we propose a micro thermal diode, in which one-way working fluid circulation is driven by wettability difference between condensation and evaporation plates. The working fluid is hermetically sealed in a micro chamber made by MEMS fabrication process which enables
the sealing structure small. The hermetic sealing can drastically reduce the gas leakage, which promises the long term reliability. In addition, the super-hydrophobic surface is not mandatory for our proposed device because the working fluid can be driven without droplet jumping. Thus, various types of working fluid can be applicable for the proposed device, even if the super-repellent surface for that fluid cannot be used. The device was fabricated on Si wafers with embedded glass microstructures, which realized high thermal insulation for reverse heat flow.

Figure 3. Surface structure of Ni/PTFE film (a) just after electroplating and annealing at 300 °C, and after (b) 30 s, (c) 1 min and (d) 3 min etching of Ni. Off time of pulsed electroplating was 2 ms.

Figure 4. Water droplet on Ni/PTFE film (a) before and after (b) 30 s, (c) 1 min and (d) 3 min etching of Ni.
2. Working principle of the micro thermal diode

2.1. Device structure and fluid circulation mechanism

Figure 1 shows the structure and working mechanism of the proposed micro thermal diode. The device consists of two Si plates: an outlet-side plate with a super-hydrophobic surface and an inlet-side plate with hydrophilic microchannels. The microchannels are filled with working fluid such as water. 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 the super-hydrophobic surface is cooled (figure 1(b)). The working fluid in the microchannels evaporates and condenses on the super-hydrophobic surface, which forms small droplets on the surface. The droplet glows by coalescing, and then returns to the microchannel when it touches to the hydrophilic surface of the microchannels. Thus, the evaporation-condensation cycle continues like a heat pipe. The evaporation-condensation rate from microchannels is known to be higher than that of pool boiling [9]. In addition, the heat transfer coefficient of drop-wise condensation is much higher than that of film-wise condensation [10]. Therefore, the overall heat transfer coefficient of this mechanism can be theoretically high. When heat transfer coefficients of evaporation from microchannels and dropwise condensation are assumed to be $3 \times 10^4 \text{ W m}^{-2} \text{ K}^{-1}$ [9] and $6 \times 10^9 \text{ W m}^{-2} \text{ K}^{-1}$ [11], respectively, the estimated overall heat transfer coefficient in forward mode is $37,500 \text{ W m}^{-2} \text{ K}^{-1}$.

On the contrary, the outlet-side plate with the super-hydrophobic surface is heated in reverse mode (figure 1(c)). The droplets of working fluid on the super-hydrophobic surface evaporates and condenses on the microchannel wall. However, the condensed liquid remains in the microchannels because of their hydrophilicity, and does not return to the heating area. Therefore, in the reverse mode, the heat mainly flows through the condenser liquid as well as the chamber wall which is made of thick glass for high thermal insulation. Thus, the overall heat transfer coefficient is estimated as $3250 \text{ W m}^{-2} \text{ K}^{-1}$, which is smaller than that in forward mode.

2.2. Numerical simulation of droplet motion

The water recycle mechanism was confirmed by a finite volume method using OpenFOAM (ver. 2.3.1) [12]. Two-phase flow consisting of the liquid and vapor of water was calculated using a volume of fluid (VOF) method. Figure 2 shows a simulation model and calculated result. The bottom boundary is treated as a solid wall with a contact angle of 150° (hydrophobic), and the top, front and back boundaries are treated as solid walls with a contact angle of 50° (hydrophilic). Both left and right boundaries are set at a constant pressure. No evaporation or condensation phenomena is considered in this simulation model. The gap between the hydrophobic and hydrophilic surface is 70 μm. The gravitational force is applied to the fluid downward. The simulation result suggests that the droplet on the hydrophobic surface moves into the microchannel with hydrophilic surface in a short time regardless of the gravity.

3. Device Fabrication

3.1. Fabrication process of super-hydrophobic surface

The super-hydrophobic surface for the outlet-side plate was formed and evaluated as follows. First, a Ni/PTFE film was deposited by electroplating using a solution consisting of 1.2 M of Ni(NH₂SO₄), 0.5 M of H₃BO₃ and 40 g l⁻¹ of PTFE particles with an average diameter of 220 nm [13]. A pulsed electroplating method was conducted on the condition that ‘on’ time was fixed at 10 ms and ‘off’ time was in a range between 2 ms and 10 ms, i.e. the duty ratio was in a range between 0.50 and 0.83. 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. After electroplating, the film was annealed at 300 °C in a vacuum furnace to form a network of PTFE, and Ni was etched by HNO₃ to make a porous PTFE surface.

Figure 3 shows the scanning electron micrographs (SEMs) of the superhydrophobic surface before and after 20 s, 1 min and 3 min etching of Ni. To evaluate the hydrophobicity, small water droplets with diameter range between 100 and 300 μm were formed on the surface using an atomizer. The contact angle was then measured by θ/2 method using an optical microscope. Figure 4 shows the water droplets on the hydrophobic surfaces, and figure 5 presents the measured contact angle of the droplet as a function of Ni etching time.

Figure 5. Measured contact angle of water droplet on Ni/PTFE film with respect to Ni etching time.
The deposition rates were 30 μm min⁻¹, 16 μm min⁻¹ and 10 μm min⁻¹ for ‘off’ times of 2, 5 and 10 ms, respectively. However, the ‘off’ time had little effect on the contact angle as shown in figure 5. Therefore, the shortest ‘off’ time (i.e. 2 ms) was selected for the following device fabrication.

3.2. Fabrication process of micro thermal diode

Figures 6–8 show the fabrication procedures of the inlet-side plate, outlet-side plates and assembly process, respectively. The inlet-side plate was fabricated as follows. First, a micromold for the glass thermal insulation structure was formed on a Si substrate (figure 6(a)). A borosilicate glass plate was anodically bonded to it at an applied voltage of 600 V, a substrate temperature of 400 °C and a vacuum level of 1.2 × 10⁻⁴ Pa (figure 6(b)), and the cavity of the micromold was sealed in vacuum. Then, the sample was heated at 900 °C under atmospheric pressure to reflow the glass into the vacuum-sealed cavity according to pressure difference (figure 6(c)) [16]. Unnecessary glass over the surface was removed by mechanical grinding and polishing (figure 6(d)). A thin film of Au and Cr was vacuum deposited (figure 6(e)) and thick photoresist was patterned on it. A thin film of Ni was electroplated using the Au/Cr film as a seed layer (figure 6(f)), and thick photoresist was patterned on it. A thin film of Au and Cu was deposited in top of the Ni structure using lift-off technique (figure 6(h)). The microchannels were formed by deep reactive ion etching (DRIE) (figure 6(i)), and the fluid charging holes were formed by DRIE from the back side (figure 6(j)). To increase the wettability, a SiO₂ thin film was deposited on the channel surface by plasma enhanced chemical vapor deposition (figure 6(k)). Finally, the unnecessary SiO₂ film was removed by reactive ion etching (figure 6(l)). Figure 9 shows the fabricated microchannels and the embedded glass thermal insulation structure. Two configurations of channels with widths of 10 μm and 100 μm, were fabricated.

For the outlet-side plate, firstly, mesa structures were formed on another Si substrate (figure 7(a)). An Cr/Au, Ni and Cu/Au films were deposited by vacuum evaporation (figure 7(b)), electroplating (figure 7(c)) and vacuum evaporation(figure 7(d)), respectively. Then, the Ni/PTFE film was deposited by the pulsed electroplating, where ‘on’ time was 10 ms and ‘off’ time was 2 ms (figure 7(e)). The film was annealed at 300 °C in vacuum, and Ni was etched by HNO₃ for 30 s to make a porous PTFE surface as described in section 3.1 (figure 7(f)). These two plates were bonded using screen-printed Pb-free solder (figure 8(a)). A Cr/Au film was deposited on the inlet-side plate (figure 8(b)), and gold stud bumps were formed near the charging holes (figure 8(c)). From the charging holes, 4 μl of water was inserted in a cavity (figure 8(d)) and sealed by crashing the gold bump (figure 8(e)) [17]. Figure 10 shows the gold bump before and after crashed.

4. Evaluation of the micro thermal diode

4.1. Experimental setup

Figure 11 shows the experimental setup for the evaluation of overall heat transfer coefficient. The heat flux was measured by a heat flux sensor (FMR-200-K, Concept Engineering GmbH, Germany) and the temperature difference was measured by
Figure 8. Assembly process.

Figure 9. Scanning electron micrograph of (a) embedded glass in Si (at fabrication step (d) in figure 6) and (b) inlet-side plate.

Figure 10. Gold stud bump (a) before and (b) after crashing.
two K-type thermocouples placed on both sides of the device. The size of the device was $10 \times 10 \times 1 \text{ mm}^3$. The device and the flux sensor were placed in between two heat conduction blocks made of brass, one of which was heated by a heater and the other was cooled by air flow. An acrylic shield was placed around the heat conduction block for thermal insulation. To improve the contact heat conductance, a high thermal conductivity rubber sheet was placed in between every components.

4.2. Overall heat transfer coefficient

The device was placed in the setup as the inlet-side plate was on the upper side for the forward mode evaluation and the lower side for the reverse mode evaluation.

Figure 12 shows the measured relationship between the heat flux, $q$, and temperature difference of the device, $\Delta T$. The signs of heat flux and temperature difference were defined as positive in forward mode operation, i.e. the heat flows from the inlet-side plate to the outlet-side plate.

The overall heat transfer coefficient, $K$, was then calculated as

$$K = \frac{q}{\Delta T}. \quad (1)$$

Figure 13 shows the obtained overall heat transfer coefficient in each mode as a function of heat flux. In reverse mode, the overall heat transfer coefficient was almost constant, which implies the heat transfer in this mode was mainly caused by heat conduction through the solid wall and vapor. However, the measured values were $4790 \pm 37 \text{ W m}^{-2} \text{K}$ for $10 \mu\text{m}$ channel width and $5840 \pm 330 \text{ W m}^{-2} \text{K}$ for $100 \mu\text{m}$ channel width, which were higher than theoretical estimation ($3250 \text{ W m}^{-2} \text{K}$). Unexpected heat loss might be caused by the bridge of solder pushed away from the bonding area.

In forward mode, the overall heat transfer coefficient had a dependency on the heat flux. The measured values ranged from $9100$ to $13300 \text{ W m}^{-2} \text{K}$. The device with smaller channel width had higher overall heat transfer coefficient especially at high heat flux region, because smaller channel width generates higher capillary force resulting in efficient working fluid circulation. However, compared with an estimated value of $37500 \text{ W m}^{-2} \text{K}$, the measured value was about $1/3$ at the maximum. This degradation of performance was considered as the effect of non-condensation gas (mainly air) encapsulated in the cavity, which prevents condensation heat transfer [18]. The positive heat flux dependency of the overall heat transfer coefficient is also considered as the effect of non-condensation gas. When the heat load increases, the effect of non-condensation gas becomes relatively small because of raised vapor pressure, which is also the case with a normal heat pipe [2].

Difference in the overall heat transfer coefficient between forward and reverse modes suggests that the working fluid returned to the microchannels against the gravity as intended. Although there were some problems as mentioned above, thermal diodicity by the proposed mechanism was demonstrated.

The performance index, which was defined as the ratio of overall heat transfer coefficient in forward and reverse modes, was calculated as $2.82 \pm 0.17$.

5. Conclusion

A micro thermal diode with a glass thermal insulation structure embedded in a vapor chamber was designed and fabricated. The fabrication processes of the glass micro structure and a porous PTFE superhydrophobic surface were developed. The proposed fabrication method enables the sealing structure
small, which increases the active area for the thermal diode especially in a small device. The hermetic sealing structure prevents gas leakage, which may increases the long-term reliability. The overall heat transfer coefficients in forward and reverse modes were measured as 13 300 W m⁻² K and 4790 ± 37 W m⁻² K, respectively. The flow direction dependency of the thermal resistance, i.e. thermal dodiocity, was demonstrated by the fabricated device, which suggested that the water circulation mechanism worked against the gravity as intended. The performance index, $K_f/K_c$, was about 2.82 ± 0.17. We used water as the working fluid. However various types of working fluid can be applicable for the proposed device even if the super-repellent surface for that material does not exist. Thus the proposed device can be applicable for various temperature range by changing the working fluid encapsulated in it.

Acknowledgments

This research was partly supported by the Creation of Innovation Centers for Advanced Interdisciplinary Research Areas Program.

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