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MEMS Silicon-Based Micro-Evaporator with Diamond-Shaped Fins

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Abstract

A new design of micro-evaporators, with 45 channels (100 µm deep) and diamond-shaped fins (40µm wide, 160µm long, 20µm separation), is fabricated by anodic bonding of silicon and glass wafers, in a five masks process. This new design improves stability of the working conditions, and has a localized hot zone in the main part of the device. The measured absorbed heat includes the energy that heats up the coolant (water) from 25 to 100 °C (roughly 300 J/g) and the latent heat of evaporation (2400 J/g). The latter one is a dominant term, and heat absorption is significantly increased at fin temperatures above the water boiling point.

Keywords: two-phase flow; heat transfer; anodic bonding

1. Introduction

An increase of the energy density in device miniaturization and chemical process intensification generates intense local heating. To deal with the high heat fluxes, properly designed devices for heat absorption (cooling) are needed. Currently, there are numerous heat exchangers and heat sinks, which either absorb the heat with single-phase flow [1] or use two phases [2], or are fabricated with solid materials such as steel or copper [3]. In applications that require internal convection cooling, with limited flow rates, e.g. in small space satellites, two-phase heat exchangers, such as evaporators, are essential.

Micro-evaporators deal with heat fluxes by evaporating the liquid flowing in micro channels [1]. The absorbed heat includes the energy that heats up the coolant to the boiling point and the latent heat of evaporation. The latter one can be a dominant term, and heat absorption is significantly increased at temperatures above the boiling point.

Recently [4], we presented silicon-silicon bonded MEMS evaporators with an array of high aspect ratio channels that acts as the finned structure. Limitations of such devices included oscillating operation in the mixed-flow (two-

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phase flow) regime, boiling before reaching the finned structure and blocking of the channels caused by the backflow of vapor bubbles.

In this paper we present a new design that uses glass instead of silicon as the bottom wafer and introduces a cavity in silicon that decreases heat losses. Also, a new layout of the channels is implemented to solve the problems caused by the water vapor backflow.

2. Design

A conceptual design of the micro-evaporator is shown in figure 1. Cold demineralized water enters the chip through the inlet, and in a divider manifold is being distributed among the mesh of channels. The heated zone is located around and above the channels in the main region. Hot water, in liquid and/or gas phase converges through the collector manifold to the outlet and leaves the device. The channels are 100 μm deep and 20μm wide at the narrowest point. To mimic processes which cause heating, a heater is integrated in the evaporator structure. The heater consists of a bulk silicon resistor, with a footprint of 2.7 mm × 2.7 mm. It is placed directly above the channels, to ensure the uniformity of the heat generation across them. This heater also serves as a temperature sensor, due to the temperature dependent electrical resistivity of silicon. Aluminum contact pads are located on the top side of the device.

In order to thermally insulate the inlet part and prevent unwanted evaporation in the divider manifold, an additional cavity is etched in silicon, leaving only 10-15 μm of silicon as the ceiling of the channels.

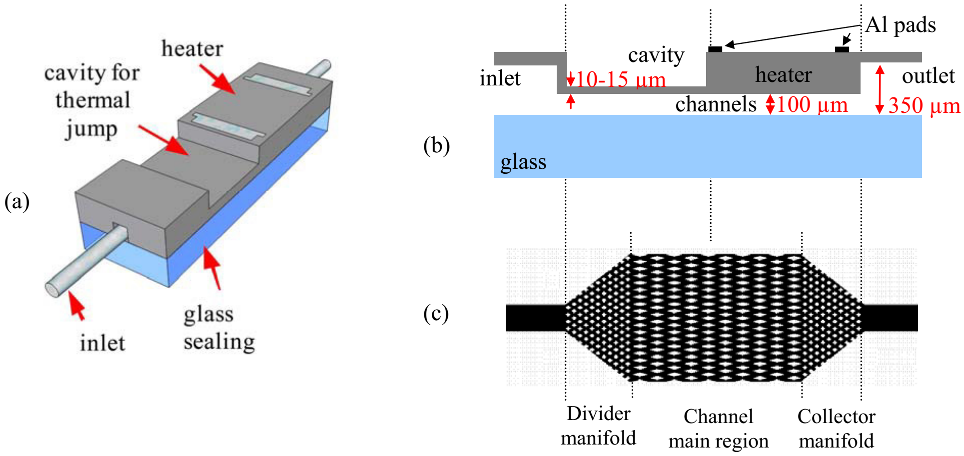


Fig. 1. (a) 3-D sketch of the device. (b) Schematic cross-section and (c) top view of the device and channels.

3. Fabrication and packaging

The micro-evaporator device was fabricated in a five masks process, starting with a p-type <100> double-side polished silicon wafer that is later joined to a glass wafer by anodic bonding. Both wafers were 500 μm thick and 100 mm in diameter. The glass wafer was not processed before the bonding.

As a first fabrication step, a 360 nm thick wet thermal oxide layer was grown on silicon wafer to protect the bonding surface during processing. On the top side of the wafer, contact holes were opened in the silicon oxide and silicon was doped by boron implantation (dose: $1.0 \cdot 10^{15}$ cm^{-2}, energy: 50 keV), to make low-ohmic contact between the aluminum thin film and the silicon bulk. After annealing for dopant activation (at 950 °C, for 20 minutes), a 1.5 μm thick aluminum layer was sputter-deposited and patterned by wet etching.

A 2.5 μm thick PECVD (plasma enhanced vapour chemical deposition) silicon oxide layer was then deposited on both sides to serve as a mask layer during etching of the structures. The 350 μm deep inlet/outlet, and 100 μm deep divider/collector manifolds and the channels were etched on the bottom side of the wafer in a two-step DRIE (deep reactive ion etching) process. Close-up SEM image of the etched pillar and channel structure is shown in figure 2.a.

Additional cavity for a more pronounced thermal gradient from the heater to the inlet was etched on the top side of the wafer. The cavity depth is 385 μm, leaving about 15 μm thick ceiling on top of the channels.

After removal of the protective silicon oxide layer on the bonding surface and additional cleaning step, wafers were aligned by hand. Bonding was done at 400 ºC, 1000 V, for 1 hour.

After the wafer bonding is performed, wafers were diced in 3.33 mm × 10 mm chips (Fig. 2.b).

The chips were glued and wire-bonded to the custom-designed printed circuit board (PCB), as shown in figure 2.c. A hole in the PCB was previously drilled, in order to allow optical access to the channels. Stainless steel tubes were glued to the access holes at the sides of the device to allow the injection of de-ionized water and the dispensing of liquid/vapour. The outer diameter of the used tubes is 350 μm.

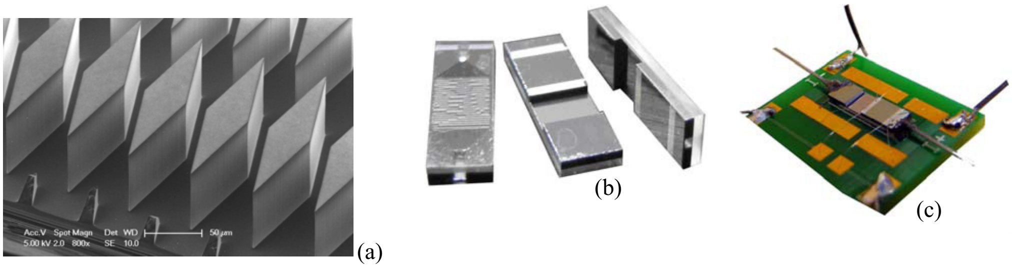


Fig. 2. (a) SEM close-up of the channel-fin structure. Diamond-shaped pillars are 100 μm high, 40 μm wide and 160 μm long. Separation is 20 μm at the narrowest point. (b) Fabricated devices (chip size is 10 mm x 3.33 mm x 1 mm). (b) Packaged devices with glued metal tubes, PCB substrate and wire-bonded and soldered electrical connections.

4. Measurement set-up

Heater calibration was performed using the probe station (Cascade Microtech 12971B), with temperature control by thermochuck Temptronic TP0315B-2. The input current and output voltage signals were provided/measured by Agilent 4156C precision semiconductor parameter analyzer.

For the electrical measurements with the flow, an electronic source HP E3631A was used as a voltage supply; the current through the heater was measured by Keithley 2700 multimeter; and the voltage across the heater was read by Fluke 8840A multimeter. Custom-made software was used to keep the temperature of the device at constant values. The flow rate was supplied by a syringe and a programmable syringe pump AL1000 connected to the device with the plastic fluidic tubes. The PCB with glued and wire-bonded device was clamped on the platform, with the glass side of the device facing upwards. An optical microscope equipped with a camera was placed above the chip.

5. Results and discussion

First, the heater resistance was calibrated as a function of temperature (Fig. 3.a). Measured data points were fitted with the second-order polynomial with RMS error less than 1 Ohm. The heater resistance was doubled in temperature range 30-130 °C.

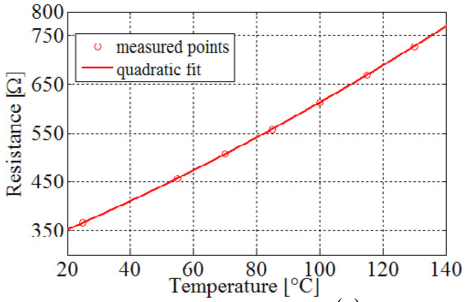
Successful leak tests were performed for the water flow rates up to 1800 g/h (limited by the syringe system).

Fluidic measurements were performed in two stages. First, without the water flow, in order to determine the heat losses by conduction and convection at different temperatures. Then, the absorbed power was calculated as the difference of the power dissipated in the device with the sustained flow and the dissipated power without water passing through the device. Tests were performed for very low flow rates up to 1 g/h of water.

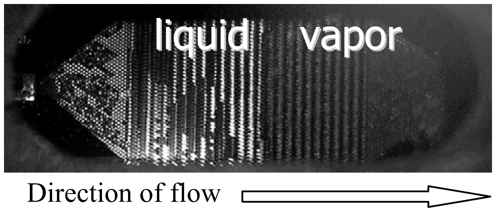
Measurements of the absorbed power proved the performance increase in the mixed-flow regime. For the tested low flow rates, absorbed power is negligible (few tens of mW) for temperatures lower than 100 °C. For higher temperatures, absorbed levels of about 0.5 W per 1 g/h flow rate were measured. When a flow is fully evaporated, a sharp liquid-vapor front is clearly visible (Fig. 3.b). This front is at the edge of the etched “thermal cavity” (Fig. 1. b-c), confirming achieved thermal insulation along the direction of flow.

No backflow of vapor bubbles was observed, indicating that the proper geometry for pillars/channels was used.

Because of the changed heat transfer coefficient for liquid and vapor, the control loop is not able to nicely follow the set point in the mixed-flow regime. This leads to the oscillatory behavior, significantly reduced compared to the devices reported in [4], but still present (the swing is ~10% of the nominal power dissipation value). A modified and more complex control loop could provide a solution for this problem.



(a)



(b)

Fig. 3. (a) Heater calibration curve. (b) Optical image during operation. At the edge of the “thermal cavity” (Fig. 1.b-c), liquid-vapor front is clearly visible, indicating good thermal insulation in the longitudinal direction.

6. Conclusions

A new design of micro-evaporators was successfully fabricated and tested. Glass bottom of the devices allowed visual inspection of the channel structure during operation. The additional thermal cavity performed as anticipated, keeping the entrance part below the boiling point of the coolant (demineralized water), whereas the heated zone was above the boiling point. Diamond-shaped pillars that act as the fins in the channel structure prevent the backflow of the vapor bubbles. The oscillatory behavior in the mixed-flow regime is still present, but this time is significantly reduced.

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