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A multi-artery vapor chamber and its performance

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HIGHLIGHTS

- A multi-artery vapor chamber is designed, built and tested in this study.
- The performance of the vapor chamber under different conditions was tested.
- The lowest measured thermal resistance is less than 0.08 K cm^2/W.
- This vapor chamber has a very good performance and easy to manufacture.

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ABSTRACT

A multi-artery vapor chamber was designed, built and tested in this study. In this vapor chamber, the wick structure consists of sintered copper powder layers on the top and bottom plates, operating as evaporator and condenser wick respectively, and sintered copper powder rings embedded with solid copper columns operating as liquid flow path. Copper powder rings contact the tip of the condenser and evaporator wicks directly to provide a short return path for the working fluid. Solid copper columns are welded together with the top and bottom plate to prevent deformation of the vapor chamber, which is caused by the internal and external pressure difference. An experimental system with joule heating and water cooling was built. Thermal resistance was defined to characterize the performance. The performance of the vapor chamber under different heat loads, heating areas and heating modes were tested and analyzed. The lowest measured thermal resistance is less than 0.08 K cm^2/W using a 1 cm^2 heat source. The maximum tested heat flux is 300 W/cm^2 without the capillary or boiling limits reached. As compared with the vapor chambers reported in the literature, this vapor chamber has a very good performance and can be easily manufactured with low cost.

1. Introduction

The microelectronic and photoelectronic industry are developing high levels of integration, high-power and high-performance, this results in a high heat flux problem which reduces the performance of chips significantly. Therefore, a component with excellent heat dissipation ability is badly needed. A vapor chamber (VC), which works on the principle of phase change, is an effective solution to this problem. Vapor chambers are heat spreaders that provide a high heat transfer coefficient, and also homogenize the temperature distribution and reduce heat centralization. A VC includes a container, a wick structure, and a vacuum chamber. The working fluid is inserted into the container and provides heat transfer by phase change. During operation, the liquid phase of working fluid is vaporized to vapor phase by absorbing heat on the evaporator wick, and the vapor moves to the condenser through the vapor core immediately. The vapor phase of working fluid is condensed to liquid phase by releasing heat on the condenser wick, and the liquid subsequently returns to the evaporator through the wick structure and is recycled again Refs. [1–3]. The wick structure ensures the circulation of the working fluid so the heat transfer continues, and also determines the evaporation and condensation efficiency. Therefore, the function of the wick structure is the main factor in the performance of a VC.

High permeability, capillary and thermal conductivity are the main requirements for VC wick. In general, there are four types of

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Nomenclature

Q	heat load, W
q	heat flux, W/cm^2
R_{VC}	thermal resistance of the VC, K/W
R^*_{VC}	equivalent thermal resistance of the VC, K cm^2/W
R_{cp}	thermal resistance of copper plate, K/W
T_j	temperature at the junction, °C
$T1-T13$	temperature measured by thermocouples, °C
$T_{ave,top}$	average temperature of the VC condenser surface, °C
A_h	heating area, cm^2
A_c	surface area of condenser, cm^2
k_v	thermal conductivity of evaporated vapor, W/m K
k_s	thermal conductivity of evaporator and condenser wall, W/m K
k_e, k_c	thermal conductivity of evaporator and condenser wick, W/m K
$\delta_{w,e}$, $\delta_{w,c}$	evaporator and condenser wick thicknesses, mm
$L_{s,e}$, $L_{s,c}$	evaporator and condenser wall thickness, mm
L_c	distance between evaporator area and condenser wick, mm
$R_{ku,c}$	surface-convection resistance of coolant stream, K/W

capillary wicks: (1) the sintered powder wick is the most conventional one which provides a large capillary force and low effective thermal resistance; (2) the mesh wick has a moderate capillary, but has low permeability and high effective thermal resistance; (3) the micro-channel wick high permeability and thermal conductivity, but its capillary is low; (4) the metal foam wick has high porosity and multiscale pore sizes which provide a high permeability. However, the performance of a wick is not only influenced by its type, but is also influenced by its structural design. Various designs of VCs are proposed in the literature.

Hwang et al. [4] designed and tested a multi-artery heat-pipe spreader VC with a monolayer evaporator wick and a set of lateral converging arteries, fabricated from sintered spherical copper particles. They also constructed another VC [5] by designing a thin evaporator wick with distributed permeable columnar arteries supplying liquid to highly concentrated heat source region. The condenser wick is composed of layered copper screens in intimate contact with the columnar arteries. The measured evaporator thermal resistance of both VCs is around 0.05 K cm^2/W. Chen et al. [6] developed a VC using diamond copper composition for the wick structure. Three different diamond-to-copper powder ratios of 1/4, 1/6 and 1/8 were used to fabricate the wick sheets and columns.

Wong et al. [7,8] studied the performance of a novel VC with parallel grooves on the inner surface of the top plate. They sintered a layer of porous wick on the bottom plate as the evaporator. The peaks of the groove walls directly contact the wick to function as liquid path, condenser and supporting structure. Zhang et al. [9] designed a novel grooved VC with radial grooves machined on the bottom plate at every 3°. The width and the depth of the grooves are 0.2 mm and 3 mm and the top end surface of the grooves touch the condensation surface.

Lu et al. [10] tested a VC using high thermal conductivity and permeability graphite foam as the wick. The VC with a traditional structure can function properly at a heat flux of 80 W/cm^2 using ethanol as the working fluid. The lowest thermal resistance obtained in the experiments is 0.4 K/W. Ji et al. [11] designed a VC with copper foam pieces that function as wick with several copper foam bars directly contacting the tip of the condenser and evaporator wicks. It can function properly at a heat flux of 216 W/cm^2, and the minimum thermal resistance is 0.09 K/W. They also designed an extended VC consisting of an evaporator part and an extended condenser part that uses copper foam for the wick [12]. A minimum thermal resistance of 0.03 K/W is reached and the heat flux is up to 450 W/cm^2 without reaching dryout.

Weibel et al. [13] designed a VC with nanostructured wicks. Carbon nanotube (CNT) arrays were used for the evaporator wick and sintered powder was used for the liquid feed wick. Their focus was on varying the macroscopic evaporator geometry to minimize flow resistance.

Although many wick structures were designed and studied, not all of the structures are suitable for industrial production. Since the sintered powder wick is already widely used in industrial production, and compares with micro grooved wicks and screen mesh wicks, the sintered powder wick is the most effective [14], it is suitable for VC industrialization. Optimization of the wick structure can improve the thermal performance of VCs. The conventional design has a long liquid flow path and weak mechanical behavior. In order to enhance the performance the VC, various kinds of columns are added to the VC. Sintered powder columns make short paths for the working fluid to return from the condensation area to the evaporation area. Solid columns can provide greater mechanical stability. Better results can be obtained if these two kinds of columns can be combined together. Min et al. [15] proposed a multi-artery heat-pipe spreader where the individual liquid arteries were designed as a wick coated solid pillar. The performance of this MAHPS was only analyzed theoretically because the structure is very hard to manufacture.

In this work, a multi-artery VC was proposed and tested. Several sintered copper powder rings embedded with solid copper columns function as liquid arteries and provide greater mechanical stability. Copper powder was sintered onto the top and bottom plate as evaporator and condenser wick. With a simple and efficient design, it not only can be easily manufactured with low cost, but also has very low thermal resistance and excellent anti-dryout characteristics. The performance of this VC was tested and compared with other VCs in the literature.

2. Vapor chamber design characteristics

Fig. 1(a) shows the components which can be combined to form a multi-artery VC, consisting of top and bottom plate, two sintered copper powder layers, copper columns and sintered copper powder rings. The VC has an area of 90 mm × 90 mm and 3 mm thickness. The top plate was formed from a 1 mm thick copper plate. A 1.5 mm deep cavity was formed and provides the chamber area for the VC. The top and bottom sintered powder layers were sintered onto the inner surface of the top and bottom plate directly. These two sintered powder layers function as the condenser wick and the evaporator wick in the VC. The copper columns consist of 28 columns which are 2 mm in diameter and 1.5 mm in height. Unlike others, these copper columns were welded onto the top and bottom plate during the pressure diffusion welding of top and bottom plate, as shown in Fig. 1(b). These columns can strengthen the structure of the VC significantly. They not only can provide better support when the inner pressure is lower than the external environment pressure, but also can help resist the expansion of the VC when the internal operating pressure is higher than the external environment pressure during operation as they are welded together with the top and bottom plate. The sintered copper powder rings were set around the copper columns, as shown in Fig. 1(b). In a conventional VC, liquid is returned from the chamber side wall to the heater location. However, the sintered copper powder rings significantly decrease the liquid flow path, helping to recycle the liquid from the condenser to the evaporator wick. The bottom plate is a copper plate with 0.5 mm