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(54) **THERMAL CONTROL LAYER IN MINIATURE LHP/CPL WICKS**

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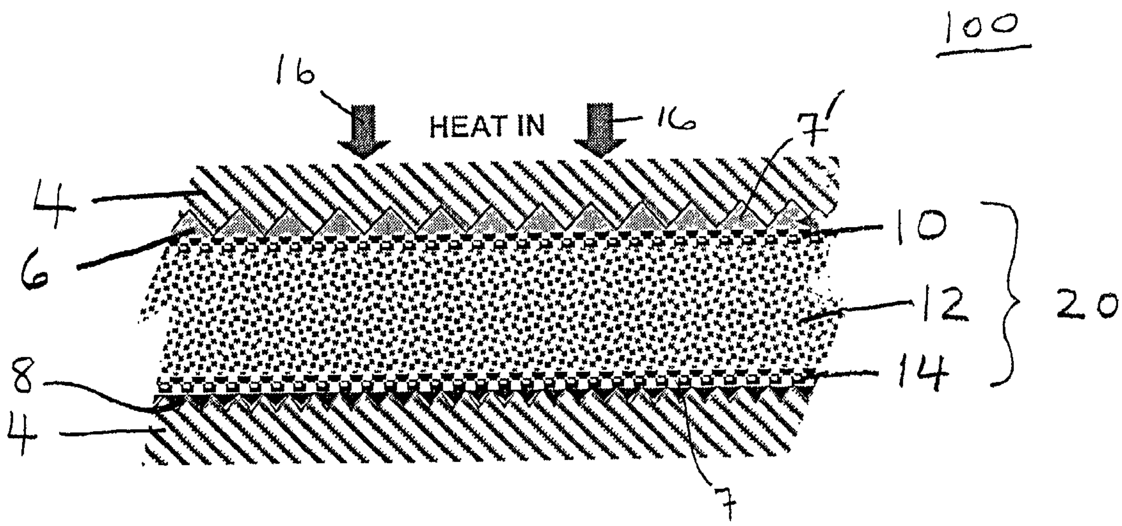
(57) **ABSTRACT**

A LHP/CPL wick includes an unconsolidated wick portion positioned within a first consolidated wick portion and a second consolidated wick portion. This wick provides a large ΔT across the wick, and sufficient capillary action for miniature LHP/CPL applications. Furthermore, the unconsolidated wick portion allows accommodation of mismatched coefficients of thermal expansion. A LHP/CPL having this wick is particularly applicable to silicon cooling devices.



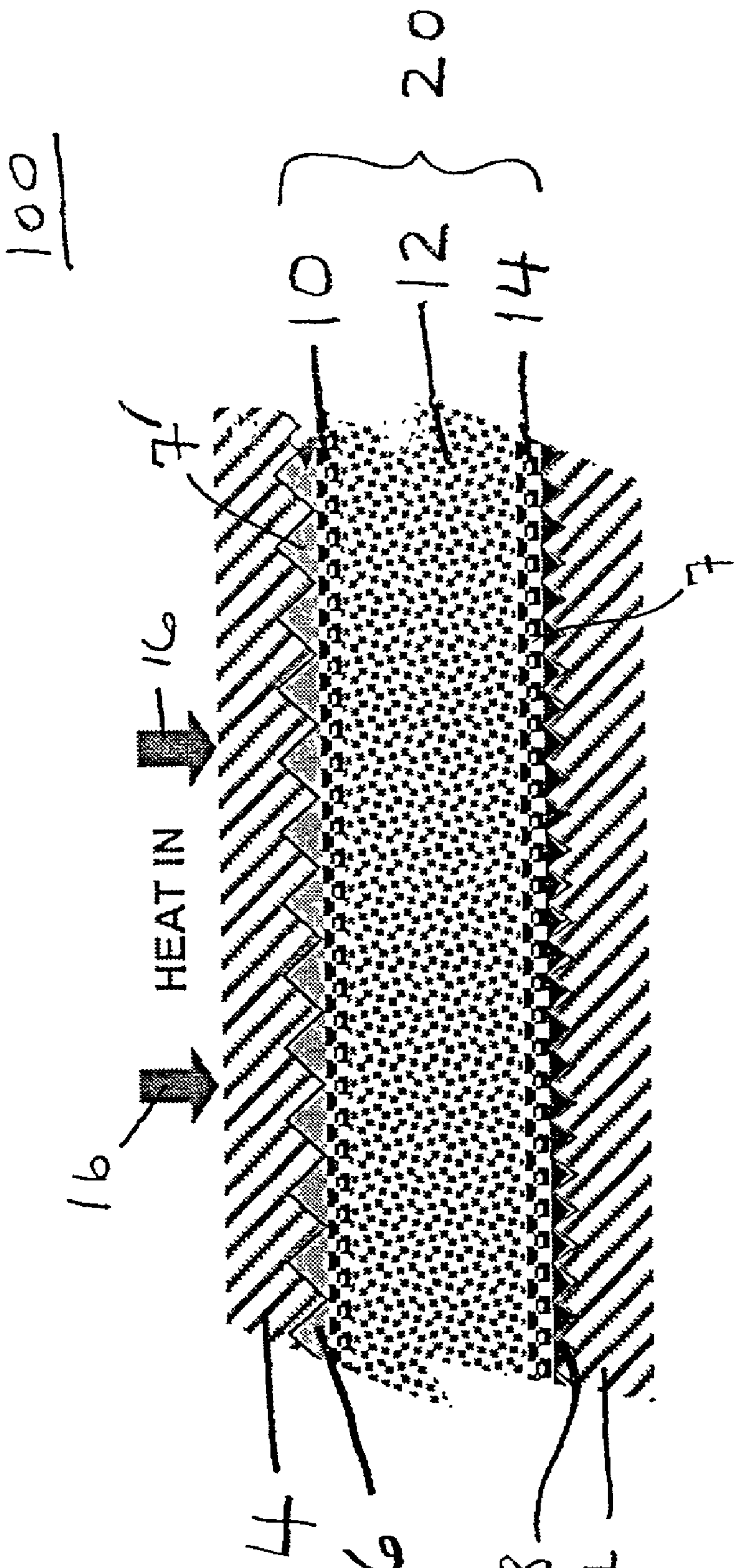


FIGURE 1

THERMAL CONTROL LAYER IN MINIATURE LHP/CPL WICKS

FIELD OF THE INVENTION

[0001] The present invention relates to loop heat pipes and capillary pumped loops, and specifically to wicks for looped heat pipes and capillary pumped loops.

BACKGROUND

[0002] The use of heat pipes is well known in the art for cooling various types of electronic devices and equipment, such as integrated circuit chips and components. A basic heat pipe comprises a closed or sealed envelope, or a chamber, containing a capillary material, such as a liquid-transporting wick, and a working fluid capable of having both a liquid phase and a vapor phase within a desired range of operating temperatures. When heat is applied from a heat source to one end of the heat pipe, the heat transfer fluid is caused to evaporate from the capillary material to absorb the latent heat of vaporization. The vapor is moved toward the other (cooled) end of the heat pipe to condense therein for the heat of condensation to be transferred to an outer heat sink through heat conduction. The condensed heat transfer fluid is absorbed by the capillary material to be moved back by virtue of a capillary pressure head toward the evaporation zone thereby completing the working cycle of the heat pipe.

[0003] Because conventional heat pipes transport liquid through the capillary wick, they incur a large flow pressure drop if they are made very long. Also, because liquid and vapor flow in opposite directions, vapor can entrain liquid at high power rates and limit the operation of the device; this is commonly known as the flooding limit. To overcome these limitations and transport high thermal power over long distances, the Loop Heat Pipe (LHP) and Capillary Pumped Loop (CPL) were developed. (See notably U.S. Pat. No. 4,515,209.)

[0004] In conventional heat pipes, heat typically enters the heat pipe from the liquid (i.e., convex) side of the meniscus. As is known in the art, the meniscus is the curved shape of the surface of a liquid in a container, caused by the cohesive effects of surface tension (capillary action). Alternatively, in capillary pumped two phase loop heat pipes, such as loop heat pipes (LHPs) and capillary pumped loops (CPLs), heat enters the device (e.g., LHP, CPL, etc.) from the vapor (i.e., concave) side of the meniscus. This is known as an inverted meniscus arrangement.

[0005] Because of the 'inverted meniscus' arrangement, devices such as LHPs and CPLs have relatively high thermal resistance in the evaporator area, and are typically not capable of operating at high heat fluxes without drying out. Conventional LHPs/CPLs typically dissipate approximately only 10 W/cm^2. One technique to improve heat flux is a method for filling the vapor spaces of the evaporator portion of the LHP/CPL with bidispersed wick in order to achieve higher heat dissipation figures. LHPs/CPLs with bidispersed wicks have achieved approximately 100 W/cm^2 of heat dissipation, however, at the expense of constricting vapor flow and maximum power capacity, as well as introducing considerable complexity and cost.

[0006] The nature of a two-phase loop requires that the temperature difference (often referred to as 'delta T' or 'ΔT') from the vapor to the liquid side of the wick correspond to the capillary pressure being produced by the wick. If the ΔT is insufficient, then boiling will occur on the liquid side of the wick and the loop will deprime (i.e., stop operating). This ΔT relationship becomes increasingly more difficult to maintain as the wick dimensions are made smaller, such as in applications with semiconductor circuits/chips and silicon compatible LHP/CPLs. Miniature evaporators for two-phase loops are thus very difficult to design and build. Furthermore, sub-miniature evaporators of a size that would permit integration with a semiconductor chip have so far not been feasible.

[0007] Therefore, there is currently a need for means for maintaining a suitable ΔT across wicks scaled to permit integration with semiconductor chips.

SUMMARY OF THE INVENTION

[0008] A wick includes an unconsolidated wick portion positioned between a first consolidated wick portion and a second consolidated wick portion.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The above and other advantages and features of the present invention will be better understood from the following detailed description of the preferred embodiments of the invention, which is provided in connection with the accompanying drawings. The various features of the drawings may not be to scale. Included in the drawing are the following figures:

[0010] **FIG. 1** is a cross sectional view of a LHP/CPL having an examplary embodiment of a wick in accordance with the present invention.

DETAILED DESCRIPTION

[0011] This description of preferred embodiments is intended to be read in connection with the accompanying drawing(s), which are to be considered part of the entire written description of this invention. In the description, relative terms such as "horizontal,""vertical,""up,""down,""top" and "bottom" as well as derivatives thereof (e.g., "horizontally,""downwardly,""upwardly," etc.) should be construed to refer to the orientation as then described or as shown in the drawing figure under discussion. These relative terms are for convenience of description and normally are not intended to require a particular orientation. Terms including "inwardly" versus "outwardly,""longitudinal" versus "lateral" and the like are to be interpreted relative to one another or relative to an axis of elongation, or an axis or center of rotation, as appropriate. Terms concerning attachments, coupling and the like, such as "connected" and "interconnected," refer to a relationship wherein structures are secured or attached to one another either directly or indirectly through intervening structures, as well as both movable or rigid attachments or relationships, unless expressly described otherwise. The term "operatively connected" is such an attachment, coupling or connection that allows the pertinent structures to operate as intended by virtue of that relationship.

[0012] Referring to **FIG. 1, a** cross sectional view of an exemplary LHP/CPL, generally designated **100**, is illustrated showing outer layers **4**, vapor channel **6**, liquid channel **8**, first consolidated wick portion **10**, second consolidated wick portion **14**, and unconsolidated wick portion **12**. The cross sectional view shown in **FIG. 1** is of an evaporator section of exemplary LHP/CPL **100**. Although not shown in **FIG. 1**, consolidated wick portions **10** and **14** enclose unconsolidated wick portion **12** such that unconsolidated wick portion **12** is contained and constrained within consolidated wick portions **10** and **14**. However, for ease of discussion, the remainder of the unconsolidated and consolidated wick portions, the condenser section, and the remainder of the LHP/CPL are not shown in **FIG. 1**. Note, the term "LHP/CPL" is used herein to refer to a loop heat pipe, a capillary pumped loop, or both.

[**0013**] LHP/CPL **100** is filled with a suitable cooling fluid **7**, e.g., water, freon, ammonia, alcohol, acetone, or some other fluid known in the art for use in heat transfer devices, and which is capable of vaporization and condensation within a closed loop environment. Parameters to be considered when selecting cooling fluid **7** include the amount of pressure that can be safely applied to the LHP/CPL **100**, the operating temperature of the equipment to be cooled (e.g., electronic device), the rate of heat transfer, the temperatures reached within the evaporator, the viscosity of coolant fluid **7**, the boiling point of coolant fluid **7**, and chemical compatibility with other materials used in the LHP/CPL. LHP/CPL **100** is sealed to the ambient atmosphere so as to form a closed loop system. As will be explained in detail, cooling fluid **7** exists in various states throughout the various sections of LHP/CPL **100**. These states include liquid, vapor, and a mixture of liquid and vapor.

[**0014**] Outer layers **4** are typically good thermal conductors, thus contributing to efficient heat exchange in the evaporator section and condenser section of the LHP/CPL **100**. Outer layers **4** may comprise any thermally conductive material. Examples of appropriate materials for outer layers **4** include metal, ceramics, ceramic compounds, and intrinsic semiconductors (i.e., undoped semiconductors) and doped semiconductor materials. Semiconductor materials may include silicon (Si), germanium (Ge), carbon (C), and tin (Sn). In an exemplary embodiment of the invention, outer layers **4** comprise silicon. A LHP/CPL **100** having outer layers **4** comprising silicon may be directly bonded to a silicon device (e.g., electronic component) for efficient cooling of the silicon device.

[**0015**] Vapor channel **6** and liquid channel **8** may comprise any structure having the capability to supply liquid and remove vapor within the evaporator. In an exemplary embodiment of the invention, vapor channel **6** and liquid channel **8** comprise separate structures (e.g., plenums, tubes, pipes) for transporting liquid and/or vapor from/to the condenser. In another exemplary embodiment of the invention (e.g., a silicon heat pipe), vapor channel **6** and liquid **8** are formed from a single structure, e.g., multiple channels, etched, molded or cut into a single or multiple blocks.

[**0016**] Wick **20** comprises first consolidated wick portion **10**, unconsolidated wick portion **12**, and second consolidated wick portion **14**. Wick **20** generates capillary pumping sufficient to maintain proper operation of the LHP/CPL **100**. Wick **20** may comprise any material and structure providing structural support, integrity (e.g., compatible coefficient of thermal expansion), and sufficient capillary action. Examples of such materials and structures include adjacent layers of metal or plastic screens, integrally formed layer of aluminum-silicon-carbide (AlSiC) or copper-silicon-carbide (CuSiC), sintered powder, sintered powder with interstices positioned between the powder particles, polymer powder, felt, ceramics, ceramic compounds, and intrinsic semiconductors and doped semiconductors. A sintered powder wick **20** may comprise materials such as metal, polymers, ceramics, plastics, intrinsic semiconductors, and doped semiconductors.

[**0017**] In an examplary embodiment of the invention, thermal energy (heat) enters outer layer **4** as indicated by arrows **16**. The heat is generated by the device being cooled, such as an electronic component. As this thermal energy is applied to the surface of outer layer **4**, working fluid **7** in the vapor channel **6** is vaporized. The working fluid **7**, in the form of vapor **7** is at a slightly higher temperature and pressure than in other areas of the LHP/CPL **100**. A pressure gradient is thus created, which forces the vapor **7** in the vapor channel **6** to flow to the cooler regions of the LHP/CPL **100** (e.g., condenser section). As the vapor **7** condenses, the latent heat of vaporization is transferred to the condenser section of the LHP/CPL **100** (condenser section not shown in **FIG. 1**). As a result, liquid forms in liquid channel **8**. The liquid in liquid channel **8** is drawn to vapor channel **6** by the capillary action of wick portions **10**, **12**, and **14**.

[**0018**] Wick **20** generates a capillary pressure, which is dependent upon the pore radius of the wick structure and the surface tension of the working fluid. During proper heat transfer, the capillary pressure generated by the wick **20** is greater than the sum of the gravitational losses, liquid flow losses through the wick, and the vapor flow losses.

[**0019**] In an examplary embodiment of the invention, dry-out is avoided by maintaining a temperature differential, ΔT, across the wick **20** sufficiently large enough to avoid the creation of nucleation sites within the wick. During normal operation, the liquid side of the wick is at a lower pressure than the vapor side. If the ΔT across the wick **20** does not compensate for this difference in pressure, boiling may occur at the liquid side of the wick. Liquid will thus be isolated from the wick, and the LHP/CPL will stop operating. Thus, a wick having good liquid permeability and providing a sufficient ΔT is desired.

[**0020**] The inventors have discovered that a wick, as depicted in **FIG. 1**, having an unconsolidated wick portion **12** positioned between first consolidated wick portion **10** and second consolidated wick portion **14** provides good liquid permeability and maintains a ΔT across the wick large enough for miniature LHP/CPL applications (e.g., applications involving electronic components). As is well understood in the art heat transfer, unconsolidated powders may exhibit greater than a factor of ten times the thermal resistance of consolidated powders. Forming unconsolidated wick portion **12** from an unconsolidated powder, or similar unconsolidated wick material, provides increased thermal resistance, which increases the ΔT across unconsolidated wick portion **12**, and thus across wick **20**. Further, the junctions between the consolidated wick portions **10**, **14**, and the unconsolidated wick portion **12** exhibit high thermal resistance. The unconsolidated powder of wick portion **12** also provides good permeability to the cooling liquid **7**. The unconsolidated powder of wick portion **12** provides a pore structure which controls nucleation sites and prevents boiling of the working fluids between the consolidated wick portions **10** and **14**. Capillary action is provided by first consolidated wick portion **10** and second consolidated wick portion **14**. Consolidated wick portions **10** and **14** comprise small uniform pores to provide efficient capillary action.

[**0021**] Unconsolidated wick portion **12** is in direct contact with consolidated wick portions **10** and **14**. The regions at which the consolidated portions and unconsolidated portion meet (e.g., the junction of sintered powder and loose powder) exhibit high thermal resistance, thus preventing all the thermal energy entering the LPH/CPL **100** via outer layer **4** from entering unconsolidated wick portion **12**. This increases the ΔT across the wick and inhibits the formation of nucleation sites. Thus, the unconsolidated wick portion **12**, positioned between first consolidated wick portions **10** and second consolidated wick portion **14**, as shown in **FIG. 1**, provides efficient capillary action and a ΔT across the wick **20** sufficient to maintain miniature LHP/CPL **100** performance.

[**0022**] A further advantage of the wick structure depicted in **FIG. 1** is that the detrimental effects upon the LHP/CPL **100** due to materials having mismatched coefficients of thermal expansion (CTEs) are reduced. This is of particular interest in semiconductor (e.g., silicon, germanium) applications in which the cooling device (e.g., LHP/CPL) is formed from the same material as the device being cooled. The use of a silicon cooling device, for example, provides good heat transfer by allowing for direct bonding to the heat generating silicon integrated circuit. However, if the CTE of the various portions of the LHP/CPL differ substantially, the LHP/CPL may be damaged by stresses causes by this mismatch during temperature fluctuations. The use of unconsolidated powders allows for a greater mismatch of CTE between various portions of the LPH/CPL and the device being cooled. Unconsolidated powder (e.g., loose powder) can accommodate mismatched CTE, thus preventing damage to the LHP/CPL.

[**0023**] In an alternate embodiment of the invention, wick **20** comprises an intrinsic or doped semiconductor, such as silicon. First consolidate wick portion **10** and second consolidated wick portion **14** comprises consolidated silicon and unconsolidated wick portion **12** comprises unconsolidated silicon. Further, outer layer **4** comprises silicon and is directly bonded to a silicon device requiring cooling, such as an electronic component. In this alternative embodiment, the first consolidated wick portion **10** may be formed as an etching on the inner surface of the outer layer **4** (e.g., etched holes). The direct bonding of outer layer **4** to the silicon device provides efficient heat transfer between outer layer **4** and the silicon device. A temperature differential, ΔT, across the wick **20**, large enough to prevent cooling fluid **7** from boiling inside of wick **20**, is provided by positioning unconsolidated silicon wick portion **12** between consolidated silicon wick portions **10** and **14**, and by the high thermal resistance exhibited at the junction between the consolidated wick portions **10** and **14**, and the unconsolidated wick portion **12**. Efficient capillary action is provided by the small and uniform pore structure of consolidated silicon wick portions **10** and **14**. Because the wick **20** and outer layer **4** comprise the same material, silicon, and because wick portion **14** comprises unconsolidated silicon, there is no mismatch in CTE.

[**0024**] As is appreciated in the art, the orientation and structure depicted in **FIG. 1** are examplary. In another embodiment, heat enters from the side opposite the side shown in **FIG. 1**, with the functional roles of channels **6** and **8** reversed. Further,

What is claimed is:

1. A wick comprising an unconsolidated wick portion positioned within a consolidated wick portion.

2. A wick in accordance with claim 1, wherein said consolidated wick portion comprises at least one of a sintered powder, a screen, and felt.

3. A wick in accordance with claim 1, wherein said consolidated wick portion is a sintered powder wick comprising a material selected from the group consisting of nickel, aluminum, silicon, germanium, a polymer, ceramic, and stainless steel.

4. A wick in accordance with claim 1, wherein said unconsolidated wick portion comprises at least one of powder and felt.

5. A wick in accordance with claim 1, wherein said unconsolidated wick portion is a powder wick comprising a material selected from the group consisting of metal, polymers, ceramics, plastics, intrinsic semiconductors, and doped semiconductors.

6. A wick in accordance with claim 1 wherein said wick comprises one of a capillary pumped loop wick and a looped heat pipe wick.

7. A wick in accordance with claim 1, wherein said unconsolidated wick portion is contained and constrained within said consolidated wick portion.

8. A heat pipe comprising:

an evaporator section;

a condenser section;

a vapor channel interconnecting said evaporator section and said condenser section in fluid communication;

a liquid channel interconnecting said evaporator section and said condenser section in fluid communication; and

a wick positioned between said liquid channel and said vapor channel, said wick comprising an unconsolidated wick portion positioned between a first consolidated wick portion and a second consolidated wick portion, wherein said first consolidated wick portion is positioned adjacent to said vapor channel and said second consolidated wick portion is positioned adjacent to said liquid channel.

9. A heat pipe in accordance with claim 8, wherein said consolidated wick portion comprises at least one of a sintered powder, a screen, and felt.

10. A heat pipe in accordance with claim 8, wherein said consolidated wick portion is a sintered powder wick comprising a material selected from the group consisting of metal, polymers, ceramics, plastics, intrinsic semiconductors, and doped semiconductors.

11. A heat pipe in accordance with claim 8, wherein said unconsolidated wick portion comprises at least one of powder and felt.

12. A heat pipe in accordance with claim 8, wherein said unconsolidated wick portion is a powder wick comprising a material selected from the group consisting of metal, polymers, ceramics, plastics, intrinsic semiconductors, and doped semiconductors.

13. A heat pipe in accordance with claim 8 further comprising an outer layer, wherein said evaporator section, said condenser section, said vapor channel, said liquid channel, and said wick are enclosed within said outer layer.

14. A heat pipe in accordance with claim 11, wherein said outer layer is directly bonded to a device for cooling said device.

15. A heat pipe in accordance with claim 14, wherein said device and said outer layer comprise the same material.

16. A heat pipe in accordance with claim 14, wherein said material comprises at least one of silicon, germanium, a polymer, ceramic, and metal.

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