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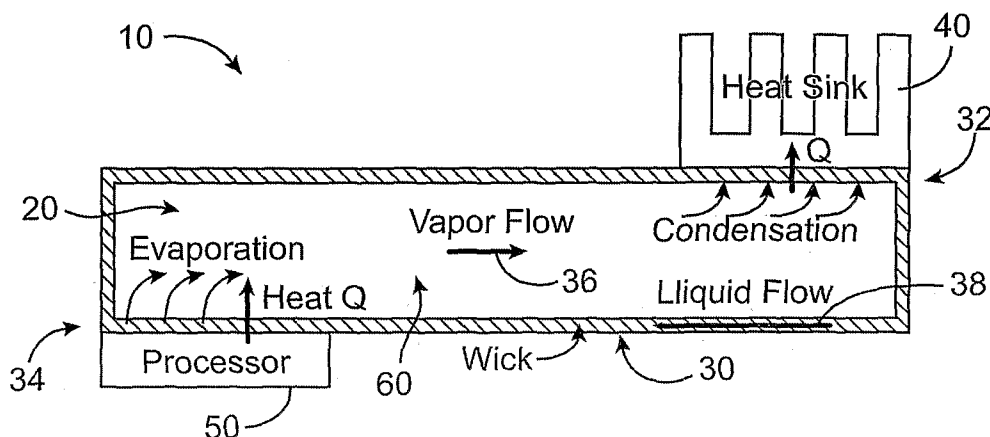
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(54) Title: NANOSTRUCTURED MICRO HEAT PIPES



(57) Abstract: A heat pipe comprising a chamber; a wick in the chamber, and a heat sink, which is adjacent to a first portion of the wick. A heat source adjacent to a second portion of the wick, wherein the wick is configured such that a gas condenses at the first portion of the wick and a liquid evaporates at the second portion of the wick. The fluid moves from the first portion of the wick to the second portion of the wick, and wherein the wick comprises nanostructures having a differentially-spaced apart gradient along the length of the wick so as to promote capillary fluid flow therealong.

## NANOSTRUCTURED MICRO HEAT PIPES

### CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Application No. 60/706,578, filed  
5 August 9, 2005, which is incorporated herein in its entirety.

### FIELD OF INVENTION

This invention relates to a nanostructured micro heat pipe, and more particularly to a  
method and system for designing and fabricating a nanostructured wick that is made using low-  
10 cost manufacturing techniques in the field of heat pipe thermal manufacturing.

### BACKGROUND

Thermal management is one of the critical issues in packaging of modern  
microelectronic processors. The increasing integration of logic and memory onto a single  
15 processor poses two challenges, namely: (1) the total power dissipation from a single processor  
is about 100 W, which produces an average heat flux of about 100 W/cm<sup>2</sup>; and (2) the peak  
power densities can increase up to 500-1000 W/cm<sup>2</sup> in the future. To dissipate this power and  
power density with a resistance at less than 0.5 K/W requires innovative solutions. The use of  
large heat sinks are precluded in many applications that rely on small volume and footprints for  
20 packaging, especially in devices having computer processors, and portable devices having  
microprocessors, such as personal digital assistants (usually abbreviated to PDAs), or other  
suitable handheld devices, and cell phones. In addition, for such applications, the demand  
performance-cost ratio of a thermal management solution is steadily increasing.

It has also becoming increasingly clear that single phase gas convective heat transfer is  
25 unlikely to be an adequate solution for such higher heat fluxes, especially when the requirement  
is for small volume solutions. In addition, single-phase liquid microchannel cooling is a  
potential solution for the average heat flux of 100 W/cm<sup>2</sup>, but cannot address the peak fluxes of  
500-1000 W/cm<sup>2</sup>. Furthermore, pumping remains a major bottleneck for reliability of  
microchannel cooling.

30 Alternatively, the latent heat of vaporization makes phase heat transfer an ideal choice  
for dissipating such high fluxes. However, two-phase convective cooling in microchannels is  
fraught with difficulties due to vapor-liquid instabilities. The only likely candidate that utilizes  
the latent heat of vaporization and requires no external power is the heat pipe. It is, therefore,  
not surprising that heat pipes have found use in most laptop thermal management.

## SUMMARY

In accordance with one embodiment, a heat pipe, comprises: a chamber; a wick in the chamber, a heat sink adjacent to a first portion of the wick; and a heat source adjacent to a second portion of the wick, wherein the wick is configured such that a gas condenses at the first portion of the wick and a liquid evaporates at the second portion of the wick, wherein fluid moves from the first portion of the wick to the second portion of the wick, and wherein the wick comprises nanostructures having a differentially-spaced apart gradient along the length of the wick so as to promote capillary fluid flow therealong.

In accordance with another embodiment, a heat dissipation system comprises: a chamber; a heat sink; a heat source; and a nanostructure array extending from the heat source.

In accordance with a further embodiment, a nanostructured composite wick comprises: a channel; and a plurality of nanostructures, wherein the nanostructures have a differentially-spaced apart gradient along the length of the channel so as to promote capillary fluid flow therealong.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a schematic diagram of a heat pipe in accordance with one embodiment.

FIG. 2 shows a schematic diagram of a thermal resistance network for the heat pipe of FIG. 1.

FIGS. 3A-3D show a schematic diagram illustrating synthesis of Cu (or other types of) nanowire arrays with controlled density and wire diameter.

FIGS. 4A and 4B show a schematic diagram illustrating synthesis of Cu (or other types of) nanowire arrays with controlled density and wire diameter as shown in FIGS. 3

FIG. 5 shows a fabrication scheme for a heat pipe using nanostructures and microchannels in accordance with one embodiment.

FIG. 6 shows a fabrication scheme for a heat pipe using nanostructures and microchannels of FIG. 5.

FIG. 7 shows a fabrication scheme for a heat pipe using nanostructures and microchannels of FIGS 5 and 6.

FIG. 8 shows a fabrication scheme for a heat pipe using nanostructures and microchannels.

FIG. 9 shows a schematic diagram of another embodiment of a heat pipe in the form of a hotspot adaptive thermal spreader.

FIG. 10 shows a schematic diagram of a nanostructured composite wick and a microchannel having a plurality of nanostructures.

FIG. 11 shows a cross sectional view of a nanostructured composite wick having a microchannel with a plurality of nanostructures.

FIG. 12 shows a schematic diagram of thermal resistance diagram of a hotspot adaptive thermal spreader.

FIG. 13 shows a cross sectional view of the glancing angle deposition (GLAD) technique for fabrication of nanowires on a substrate.

## 10 DETAILED DESCRIPTION

FIG. 1 shows a schematic diagram of a heat pipe 10 in accordance with one embodiment using a nanostructured wick 30. The heat pipe 10 includes a chamber 20; a wick 30 in the chamber 20, a heat sink 40 adjacent to a first portion 32 of the wick 30, and a heat source 50 adjacent to a second portion 34 of the wick 30. The wick 30 is configured such that a vapor or gas 36 condenses at the first portion 32 of the wick 30 and a liquid or fluid 38 evaporates at the second portion 34 of the wick 30, wherein the liquid or fluid 38 moves from the first portion 32 of the wick 30 to the second portion 34 of the wick 30, and wherein the wick 30 comprises nanostructures 70 (FIG. 6) having a differentially-spaced apart gradient along the length of the wick 30 so as to promote capillary fluid flow therealong. It can be appreciated that the chamber 20 includes a substance 60 in the chamber 20, the substance 60 changing from gas phase 36 to liquid phase 38 at the first portion 32 of the wick 30 and from liquid phase 38 to gas phase 36 at the second portion 34 of the wick 30.

FIG. 2 shows a schematic diagram of a thermal resistance network for the heat pipe 10 of FIG. 1. As shown in FIG. 2, the thermal resistance network comprises a heat source 50 (processor) - heat pipe 10 interface (R1), a wick 30 (R2), a vapor 36 (R3), the wick 30 (R4), the heat pipe 10 - heat sink 40 interface (R5), and the axial connection (R6). It can be appreciated that the power dissipated is equal to  $Q = m h_{fg}$ , where  $m$  is the mass flow rate and  $h_{fg}$  is the latent heat of vaporization. It can also be appreciated that the mass flow rate will typically depend on two factors: (1) the pressure drop in the vapor flow 36; and (2) the capillary pressure gradient in the wick 30 that drives the liquid flow 38. However, the capillary pressure gradient in the wick 30 that drives the liquid flow 38 is often the main bottleneck in improving the performance of a heat pipe 10. Hence, the design of the wick 30 can be critical for determination of the mass flow rate. The design of the wick 30 also controls the thermal resistances (R2 and R4) in the resistance network. Thus, the lower resistance is clearly preferable.

Typically, heat pipes 10 use a porous wick 30 made by sintering copper (Cu) particles, wherein, the pore sizes, (r) are generally 10-20  $\mu\text{m}$  in size. In addition, assuming water is the working substance or fluid 60, and given that the surface tension of water is 0.07 N/m, the capillary pressure that such pore sizes (r) can generate is about  $P_c = 2\sigma / r = 14 \text{ kPa}$ . However, the difference in capillary pressure between the wick region and the condensing region drives the flow. Therefore, one would grade the pore sizes in a heat pipe 10, i.e., smallest pores near the evaporator (heat source 50) and the largest pores near the condenser (heat sink 40). However, most heat pipes 10 usually do not employ graded pore sizes along the length of the heat pipes 10, although companies, such as Thermacore, have proposed such designs.

In addition, despite the use of copper (Cu), the sintered porous heat pipes 10 pose significant thermal resistance due to the presence of multiple interfaces in the heat flow path. It can also be appreciated that a reduction of the thermal resistance due to the presence of multiple interfaces can play a significant role in the overall thermal performance.

FIGS. 3A-3D show the schematic diagram of a method and process for the manufacturing of a nanostructure 70 in the form of a nanowire 100. It can be appreciated that the heat pipe 10 having a nanostructure 70 can be formed by one or a combination of the following processes: (i) grow nanowires on a porous template, e.g., electrochemical deposition of nanowires in alumina template; or (ii) direct deposition of nanowires on a substrate, e.g., GLAD technique (FIG 13).

FIGS. 3A-3D show a method of growing nanowires on a porous template, which can be formed by one or a combination of the following processes directly depositing a nanoporous film on a substrate; depositing a solid film on a substrate and then electrochemically etching the solid film forming arrays of nano-pores 92; and/or electrochemically growing nanowires or nanotubes in the nano-pores; annealing the nanowires 100 to form polycrystalline wires; and etching the film away leaving a nanowire array 110.

As shown in FIG. 3A, an aluminum (Al) film 80 of 1-10 mm in thickness 82 is deposited onto a silicon (Si) or copper (Cu) substrate 84.

FIGS. 3B and 4A show a highly ordered hexagonal array 90 of alumina nanopores 92, which are obtained by anodic oxidation of the Al film 70. It can be appreciated that the pore size and periodicity can be controlled by the electrolyte used in the anodization process. As shown in FIGS. 3B and 4A, the hexagonal array 90 of nanopores 92 shows a high degree of ordering over area of approximately  $1 \text{ cm}^2$ .

FIGS. 3C and 4B show that using the porous alumina 80 as a template, copper (Cu) nanowires 100 can be electrochemically grown in the nanopores 92 and then annealed to form a polycrystalline wire.

As shown in FIG. 3D, the alumina 80 can then be etched away, leaving the nanowires array 110. It can be appreciated that the method as described, the nanostructures 70 can be an array of nanowires 100, nanopores 92, nanotubes, or any nanoscale protrusions.

It can be appreciated that the copper (Cu) nanowires 100 serve two purposes, namely: (1) as fins for efficient heat conduction with low thermal resistance between the heat pipe surface to liquid, and (2) for creating high capillary pressure gradients for increased mass flow. In addition, the capillary pressure difference can be generated by modulating the inter-nanowire 100 spacing along the length of the heat pipe 10, and by controlling the anodization conditions. For example, nanowire 100 spacing of 20-500 nm can be designed, and assuming water as the working fluid, the corresponding capillary pressure can range from about 0.1 to 1 Mpa. It can be appreciated that the method as described above can produce a low-cost manufacturing process, which allows one to create a capillary pressure gradient from 0.1 to 1 Mpa over a 1 cm length, which is several orders of magnitude higher than what is currently used.

Alternatively, in another embodiment, microchannels 120 can be fabricated using a transport liquid 130. FIGS. 5-7 show a fabrication process in which the region to be cooled has copper (Cu) nanowires 100, and wherein the heat sink 40 has microchannels 120. As shown in FIG. 5, a silicon wafer 130 is etched forming a plurality of partial chambers 20. As shown in FIG. 6, fabricated nanostructures 70 are then added to the chambers 20, which is then filled and bonded with a silicon wafer 130 with microchannels 120 as shown in FIG. 7. It can be appreciated that since the mass flow rate is proportional to  $D^4$  for pressure-driven flow, where  $D$  is pore/channel size, a plurality of microchannels 120 will reduce the pressure drop. At the same time, the plurality of nanowires 70 will increase capillary pressure difference, considerably increasing the mass flow rate.

FIG. 8 shows a heat source 50 with a plurality of nanostructures 100. As shown in FIG. 8, the heat pipe 10 includes a plurality of microchannels 120 with a capillary pressure gradient. It can be appreciated that by incorporating nanostructures 70 in the form of nanowires 100, nanopores 92, nanotubes, or any nanoscale protrusions can enable the heat pipe 10 to be miniaturized, offering the promising prospects of high performance thermal management at low cost for portable and handheld devices.

FIG. 9 shows another embodiment of a heat pipe 10 in the form of a hotspot adaptive thermal spreader (HATS) 200, which is designed to remove hotspots and make a compact heat

sink. As shown in FIG. 9, the thermal spreader 200 includes a nanostructured vapor chamber 210, which is comprised of a plurality of sub-vapor chambers 220, and a hotspot or heat source 230, such as a microprocessor. Each of the sub-vapor chambers 220 includes a plurality of channels or microchannels 240, which are configured to converging mass flow to the hotspot 230. The microchannels 240 are preferably comprised of a nanostructured composite wick 30 as shown in FIG. 11. It can be appreciated that by providing nanostructures 70 within the microchannels 240, the capillary pressure scales as approximately  $1/r$ , which increases the capillary limit of the heat pipe 10. In addition to increasing capillary pressures, the embedded nanostructures 70, cause the mass flow rate to be predominantly determined by the microchannel 240 size.

FIG. 10 shows a coordinate for the analysis on a nanostructured composite wick 30 (FIG. 11). As shown in FIG. 10, the hotspot 250 is located in the center of the coordinate, where  $L$  is a length of the channel 240 and  $l$  is the radius of the hotspot 230. In accordance with one embodiment, it can be appreciated that the nanostructured composite wick 30 can be only on the channel 240 and preferably includes embed nanowires 100 (FIG 3C), which are located only on the hotspot area 250. It can be appreciated that the wick 30 is preferably a composite wick since it is a combination of a channel or microchannel 240 with an angle of approximately  $2\alpha$ , and nanowire arrays 110 on the channel 240 approximated as a 'small-angle-channel' with angle of  $2\beta$ . For a steady viscous flow in a convergent channel, i.e. Jeffrey – Hamel flow, the fluid velocity is a function of  $r$  only.

It can be appreciated that to enhance the performance of the heat pipe 10, an increase in mass flow is critical since the heat flow rate is related to the mass flow as  $\dot{Q} = \dot{m}_{\max} h_{fg}$ . Considering limitations due to wicking, the pressure drop due to a capillary force can be expressed is:

$$\Delta P_{\text{capillary}} = \underbrace{\Delta P_{\text{gravity}}}_{\text{neglect}} + \Delta P_{\text{liquid}} + \underbrace{\Delta P_{\text{vapor}}}_{\text{neglect}}$$

wherein an average pressure drop in the big channel based on the Jeffrey – Hamel flow is,

$$\frac{dp_{\alpha}}{dz} = \frac{2\mu\dot{m}_{\alpha}}{\rho\alpha L^3 H} \left( \frac{\tan(2\alpha)/2\alpha}{\tan(2\alpha)/2\alpha - 1} \right) = \frac{2\mu\dot{m}_{\alpha} C_{\alpha}}{\rho\alpha L^3 H}$$

where  $\rho$ ,  $\mu$  are density and viscosity respectively.  $H$  is height of the channel. Pressure drop in the nanowire arrays 110, i.e. the small-angle-channel, is,

$$\frac{dp_\beta}{dz} = \frac{2\mu\dot{m}_\beta C_\beta}{\rho\beta L^3 h}$$

where  $h$  is height of the nanowires 100. Assuming the pressure drop in the channel is the same as the one in the nanowire arrays 110,

$$\begin{aligned}\frac{dp_\beta}{dz} &= \frac{dp_\alpha}{dz} \\ \frac{\dot{m}_\beta}{\dot{m}_\alpha} &= \frac{C_\alpha}{C_\beta} \frac{\beta h}{\alpha H}\end{aligned}$$

Let  $\Phi$  be a filling factor and  $n$  be the number of small-angle-channels, i.e. nanowire arrays 110,

$$\alpha\phi = \beta n$$

Total mass flow rate in the nanostructured composite wick,  $\dot{m}_c$ , is

$$\dot{m}_c = \dot{m}_\alpha + n\dot{m}_\beta = \dot{m}_\beta \left( \frac{\alpha\phi}{\beta} + \frac{\dot{m}_\alpha}{\dot{m}_\beta} \right)$$

Now, the capillary limitation, can be written as

$$\begin{aligned}\frac{2\sigma}{l\beta} &= \frac{\mu C_\beta}{\rho\beta h} \frac{\dot{m}_c}{\left( \frac{\alpha\phi}{\beta} + \frac{\dot{m}_\alpha}{\dot{m}_\beta} \right)} \left[ \frac{1}{l^2} - \frac{1}{(l+L)^2} \right] \\ \dot{m}_c &\leq \left( \frac{\alpha\phi}{\beta} + \frac{\dot{m}_\alpha}{\dot{m}_\beta} \right) \frac{h}{C_\beta}\end{aligned}$$

where  $\sigma$  is surface tension. The capillary limitation of a homogenous channel can be written as,

$$\begin{aligned}\frac{2\sigma}{l\alpha} &= \frac{\mu C_\alpha}{\rho\alpha(h+H)} \dot{m}'_\alpha \left[ \frac{1}{l^2} - \frac{1}{(l+L)^2} \right] \\ \dot{m}'_\alpha &\leq \frac{(h+H)}{C_\alpha}\end{aligned}$$

Finally, ratio between mass flow of the nanostructured composite wick 30 and that of the homogenous channel is:

$$\begin{aligned}\frac{\dot{m}_c}{\dot{m}'_\alpha} &= \left( \frac{\alpha\phi}{\beta} + \frac{\dot{m}_\alpha}{\dot{m}_\beta} \right) \frac{h}{(h+H)} \frac{C_\alpha}{C_\beta} \\ &= \underbrace{\frac{\alpha\phi}{\beta} \frac{h}{(h+H)} \frac{C_\alpha}{C_\beta}}_{>0} + \underbrace{\frac{H}{(h+H)} \frac{\alpha}{\beta}}_{>1, \text{ if } h \ll H} > 1\end{aligned}$$

As long as height of the nanowires 100 is much shorter than that of the channel ( $h \ll H$ ),  
 5 the mass flow of the nanostructured composite wick 30 is always greater than that of the  
 homogeneous channel. In other words, height,  $H$ , and width,  $\alpha$ , of the channel 240 should be  
 large for a small liquid pressure drop and distance between nanowires 100 should be small  
 (small  $\beta$ ) for a large capillary force. For example, if the angle,  $\alpha$ , is 20 degrees and a mean  
 spacing between nanowires 100,  $2\beta A$  is approximately 200 nm, where  $A$  is around 0.5 mm (a  
 10 radius of the hotspot 230), then,  $\beta$  is approximately 0.01 degrees, so the resulting enhancement is  
 around 200.

FIG. 11 shows a nanostructured composite wick 30 having a channel or microchannel  
 240 with a plurality of nanostructures 70, preferably in the form of a nanowire 100. As shown  
 in FIG. 11, the diameter of the nanowire 100 is  $a$ , and accordingly, it can be appreciated that the  
 15 surface roughness can enhance the hydrophilicity of the hydrophilic surfaces. More specifically,  
 a contact angle,  $\theta$ , can be expressed as:

$$\cos \theta = \left\{ 1 + 4 \cdot \left( \frac{h}{a} \right) \left[ \frac{1}{\left( \frac{2\beta A}{a} + 1 \right)^2} \right] \right\} \cos \theta_e$$

where  $\theta_e$  is the equilibrium contact angle of the liquid drop on a flat surface made of the surface  
 material. To enhance the contact angle, it can be appreciated that it is preferably that the  
 20 microchannel 240 includes:

1. a large  $h/a$
2. a small  $2\beta A/a$

In addition, as our previous calculation suggests:

3. a small  $2\beta A$  is preferred for large capillary force.
- 25 4. a small  $h$  is preferential based on the equation for the ratio between mass flow of  
 the nanostructured composite wick 30 and the that of the homogenous channel 240.

In addition, it can be appreciated that in order to have a large  $h/a$  with a small  $h$ , the diameter of the nanostructure 70 or nanowire 100 in FIG. 11 should be small. At the same time, the diameter of the nanostructure 70 or nanowire 100 should be larger or at least comparable to the spacing between the nanostructure 70 or nanowires 100,  $2\beta A$ , to meet the requirements 2 and

3. It can also be appreciated that silicon (Si) nanowires 100 can also be grown using a Vapor-Liquid-Solid mechanism.

FIG. 12 shows a schematic diagram of thermal resistance of a hotspot adaptive thermal spreader 200. The thermal spreader 200 is comprised of a vapor chamber 210 for heat spreading and a plurality of microchannels 240. As shown in FIG. 12, the thermal spreader 200 includes a silicon (Si) (or Cu or any other) substrate 260 ( $R_1$ ), a nanowire 100 with a liquid ( $R_2$ ), a chamber 210 ( $R_3$ ), and a silicon (or Cu or any other) substrate 260 ( $R_4$ ) having a plurality of microchannels 240 ( $R_5$ ). As set forth below, each of the thermal resistances have a unit of  $\text{cm}^2 \text{K/W}$ .

Table 1 -  $R_1$  [ $\text{cm}^2 \text{K/W}$ ]

| Thickness [ $\mu\text{m}$ ] | k of Si [ $\text{W/mK}$ ] | R [ $\text{cm}^2 \text{K/W}$ ] |
|-----------------------------|---------------------------|--------------------------------|
| 400                         | 140                       | 0.0286                         |

Usually, the thickness of the silicon (Si) substrate 260 is around  $500 \mu\text{m}$ , however, it can be appreciated that about  $100 \mu\text{m}$  is typically etched away for vapor flow.

Table 2 -  $R_2$  [ $\text{cm}^2 \text{K/W}$ ]

| Liquid level [ $\mu\text{m}$ ] | Nanowire filling factor | Effective k [ $\text{W/mK}$ ] | k of water [ $\text{W/mK}$ ] | R [ $\text{cm}^2 \text{K/W}$ ] |
|--------------------------------|-------------------------|-------------------------------|------------------------------|--------------------------------|
| 20                             | 0.3                     | 42.42                         | 0.6                          | 0.0047                         |

This assumes steady-state operation. The liquid level is preferably thinner, which provides a small thermal resistance. At  $t=0$ , the water level is expected to be higher than  $20 \mu\text{m}$ .

Table 3 -  $R_4$

| Thickness [ $\mu\text{m}$ ] | R [ $\text{cm}^2 \text{K/W}$ ] |
|-----------------------------|--------------------------------|
| 100                         | 0.0071                         |

$R_4$  represents thickness of the Si layer. Here, we assume that channel height of the microchannel is around  $400\text{ }\mu\text{m}$ . So, the thickness of the Si layer is around  $100\text{ }\mu\text{m}$ .

Table 4 -  $R_5$ 

| $h\text{ [W/m}^2\text{K]}$ | $R\text{ [cm}^2\text{ K/W]}$ |
|----------------------------|------------------------------|
| 1587450.787                | 0.0063                       |

This heat transfer coefficient is based on our calculation. The thickness of channel 240 and wall is set to  $10\text{ }\mu\text{m}$  and  $10\text{ }\mu\text{m}$  respectively.

Table 5 Overall thermal resistance based on Si-HATS.

| $R$                | $\text{[cm}^2\text{ K/W]}$ |
|--------------------|----------------------------|
| $R_1$              | 0.0286                     |
| $R_2$              | 0.0047                     |
| $R_4$              | 0.0071                     |
| $R_5$              | 0.0063                     |
| $R_{\text{total}}$ | 0.0467                     |

As shown in Table 5, the biggest resistance comes from the silicon (Si) substrate 260. Therefore, it can be appreciated that the silicon (Si) substrate 260 can be replaced with a copper (Cu) plate or substrate. The overall thermal resistance calculation for a copper plate or substrate and a hotspot adaptive thermal spreader (HATS) is shown in Table 6.

Table 6 Overall thermal resistance based on Cu-HATS

| $R$                | $\text{[cm}^2\text{ K/W]}$ |
|--------------------|----------------------------|
| $R_1$              | 0.0100                     |
| $R_2$              | 0.0017                     |
| $R_4$              | 0.0071                     |
| $R_5$              | 0.0063                     |
| $R_{\text{total}}$ | 0.0251                     |

As shown in Table 5 and Table 6, it can be appreciated that a reduction in the thermal resistance can be achieved by replacing the silicon (Si) HATS 200 with a copper (Cu) HATS 200. It can be appreciated that in order to achieve a copper (Cu) HATS, it is necessary to

fabricate the growing copper (Cu) nanowires on a copper (Cu) plate. In accordance with one embodiment, a glancing angle deposition (GLAD) technique 300 as shown in FIG. 13 can be used. Alternatively, an electrochemical deposition of copper (Cu) on a porous alumina template as shown in FIGS. 3A-3D and 4A-4B can be used.

5           FIG. 13 shows a cross sectional view of the glancing angle deposition (GLAD) technique 300 for fabrication of nanowires 100 on a substrate 260. As shown in FIG. 13, a substrate 260 is positioned at an oblique angle relative to the incident vapor flux. If the incident flux does not have enough mobility, the flux would stay on the point where it sits on the substrate 260. Due to the oblique angle, this leads to an effect called atomic shadowing. Therefore, a columnar  
10       structure can be obtained in this way. It can be appreciated that the substrate is preferable a silicon (Si) substrate, for epitaxial growth of the copper (Cu) nanowire 100. However, it can be appreciated that a single-crystal silicon substrate 260 is not necessary, and any suitable substrate material can be used, including fabricating of copper (Cu) nanowires on a copper (Cu) plate or substrate 260.

15           While this invention has been described with reference to the preferred embodiment described above, it will be appreciated that the configuration of this invention can be varied and that the scope of this invention is defined by the following claims.

## WHAT IS CLAIMED IS:

1. A heat pipe, comprising:  
a chamber;  
a wick in the chamber,  
5 a heat sink adjacent to a first portion of the wick; and  
a heat source adjacent to a second portion of the wick, wherein the wick is configured such that a gas condenses at the first portion of the wick and a liquid evaporates at the second portion of the wick, wherein fluid moves from the first portion of the wick to the second portion of the wick, and wherein the wick comprises nanostructures having a differentially-spaced apart  
10 gradient along the length of the wick so as to promote capillary fluid flow therealong.
2. The heat pipe of claim 1, further comprising:  
a substance in the chamber, the substance changing from gas phase to liquid phase at the first portion of the wick and from liquid phase to gas phase at the second portion of the wick.  
15
3. The heat pipe of claim 1, wherein the nanostructures comprise:  
an array of nanowires, nanopores, nanotubes, or any nanoscale protrusions.
4. The heat pipe of claim 1, wherein the nanostructures are formed by one or a  
20 combination of the following processes:  
directly depositing a nanoporous film on a substrate;  
depositing a solid film on a substrate and then electrochemically etching the solid film forming arrays of nano-pores;  
electrochemically growing nanowires or nanotubes in the nano-pores;  
25 annealing the nanowires to form polycrystalline wires;  
etching the film away leaving a nanowire array; and/or  
direct deposition of nanowires on a substrate.
5. The heat pipe of claim 4, wherein the nanostructure size and density are  
30 determined by the manufacturing process.
6. The heat pipe of claim 1, wherein the nanostructures are spaced between 20 nm to 500 nm apart from one another.

7. The heat pump of claim 1, wherein the nanostructures are spaced farther apart at the first portion of the wick and closer together at the second portion of the wick.

8. A heat dissipation system, comprising:

a chamber;

a heat sink;

a heat source; and

a nanostructure array extending from the heat source.

9. The heat dissipation system of claim 8, further comprising:

a plurality of channels in the heat sink.

10. The heat pipe of claim 1, wherein the wick has a capillary pressure between 0.01 MPa to 100 MPa.

11. A nanostructured composite wick comprising:

a channel; and

a plurality of nanostructures, wherein the nanostructures have a differentially-spaced apart gradient along the length of the channel so as to promote capillary fluid flow therealong.

12. The wick of claim 11, wherein the nanostructure size and density are determined by the manufacturing process.

13. The wick of claim 11, wherein the nanostructures are spaced between 20 nm to 500 nm apart from one another.

14. The wick of claim 11, further comprising a heat source adjacent to a second portion of the wick, wherein the wick is configured such that a gas condenses at the first portion of the wick and a liquid evaporates at the second portion of the wick, wherein fluid moves from the first portion of the wick to the second portion of the wick, and wherein the nanostructures are spaced farther apart at a first portion of the wick and closer together at a second portion of the wick.

15. The heat pipe of claim 14, further comprising:

a substance in the chamber, the substance changing from gas phase to liquid phase at the first portion of the wick and from liquid phase to gas phase at the second portion of the wick.

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16. The heat pipe of claim 11, wherein the nanostructures comprise:

an array of nanowires, nanopores, nanotubes, or any nanoscale protrusions.

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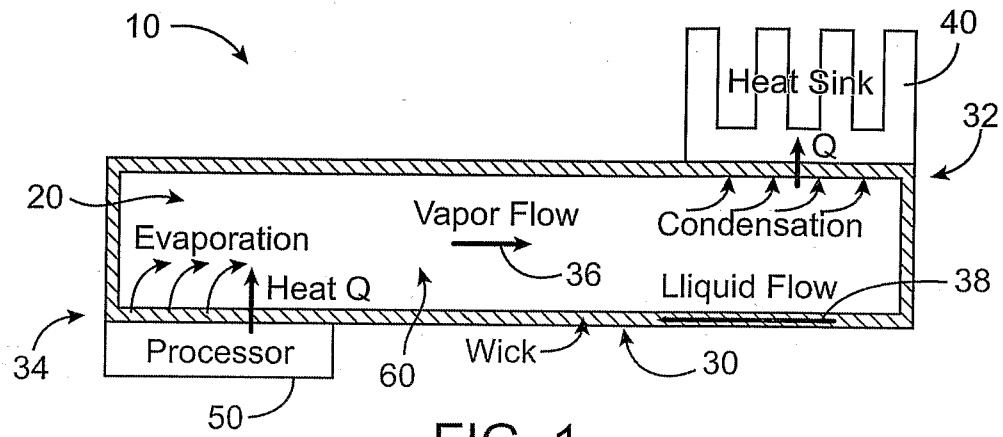


FIG. 1

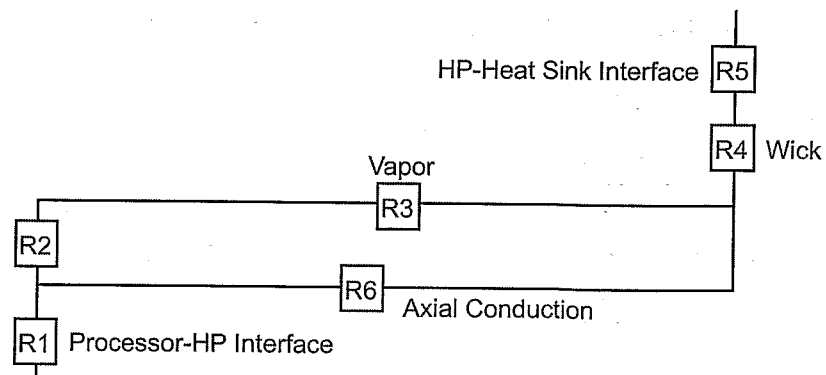
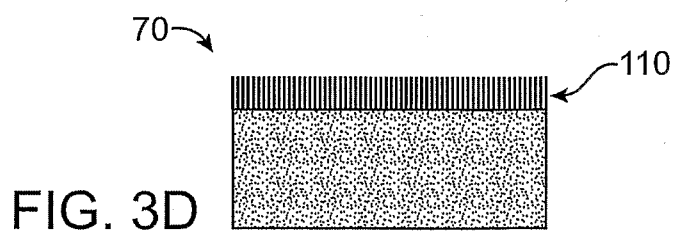
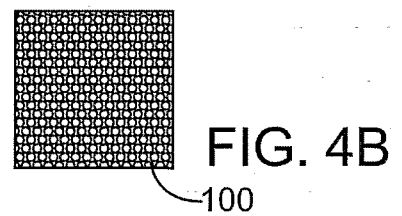
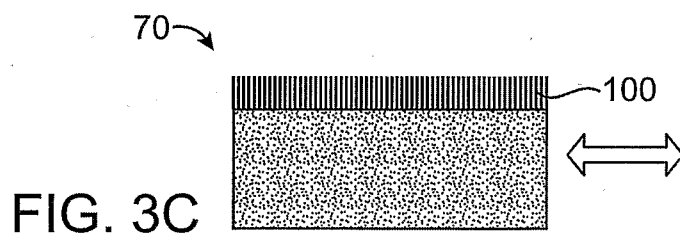
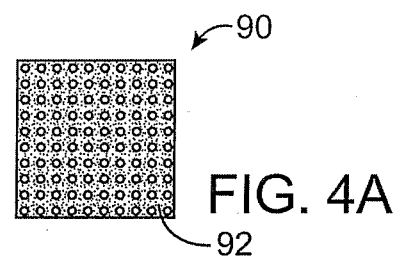
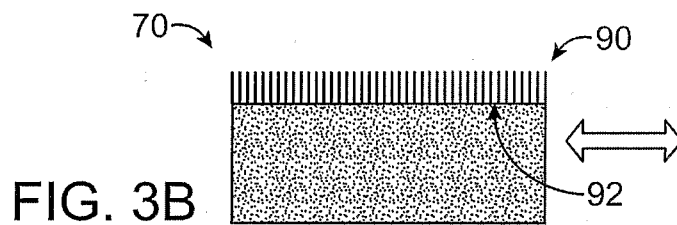
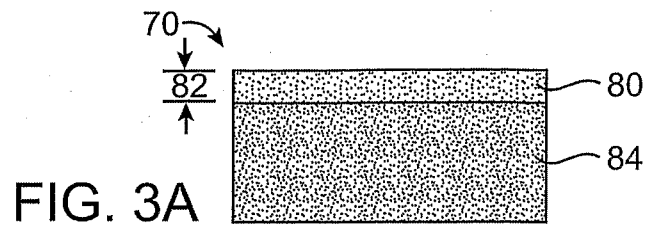
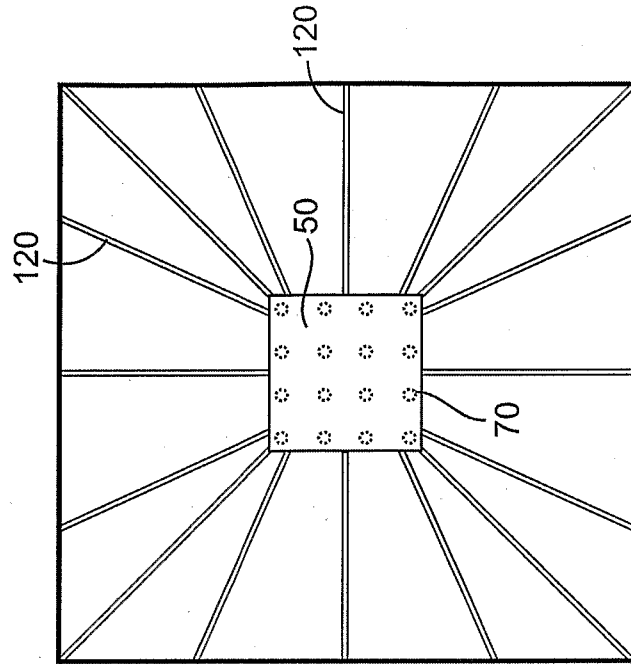
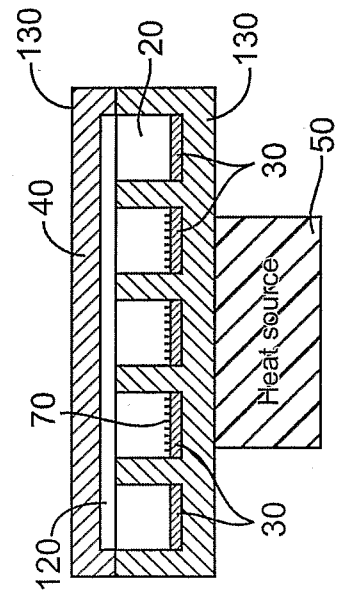
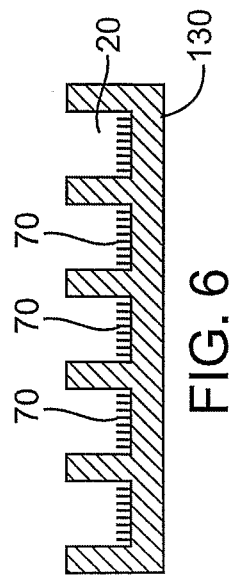
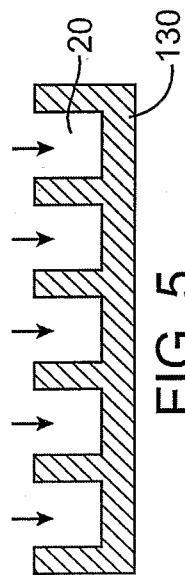


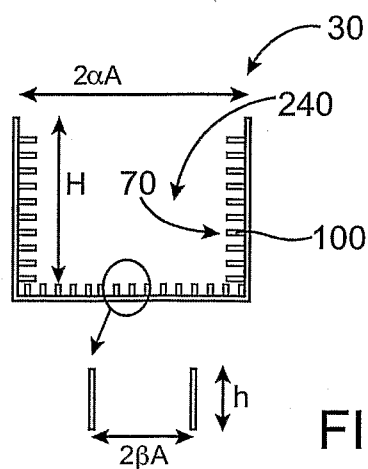
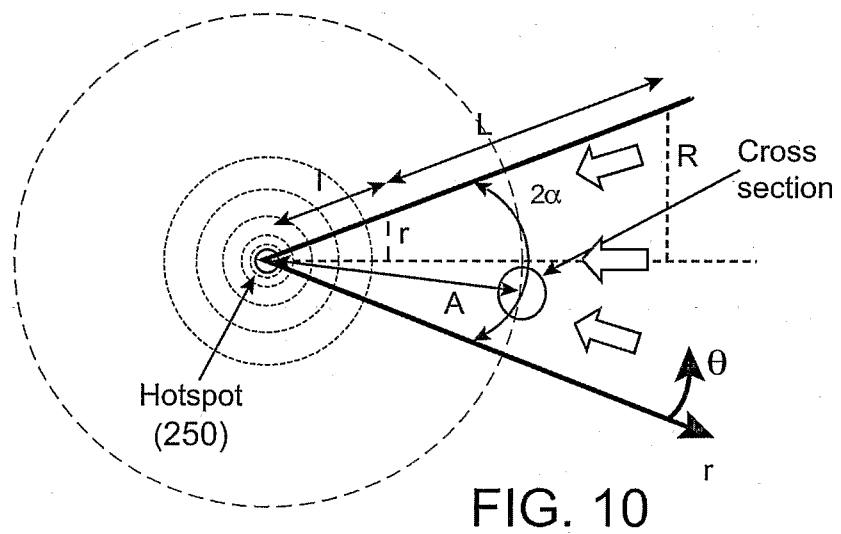
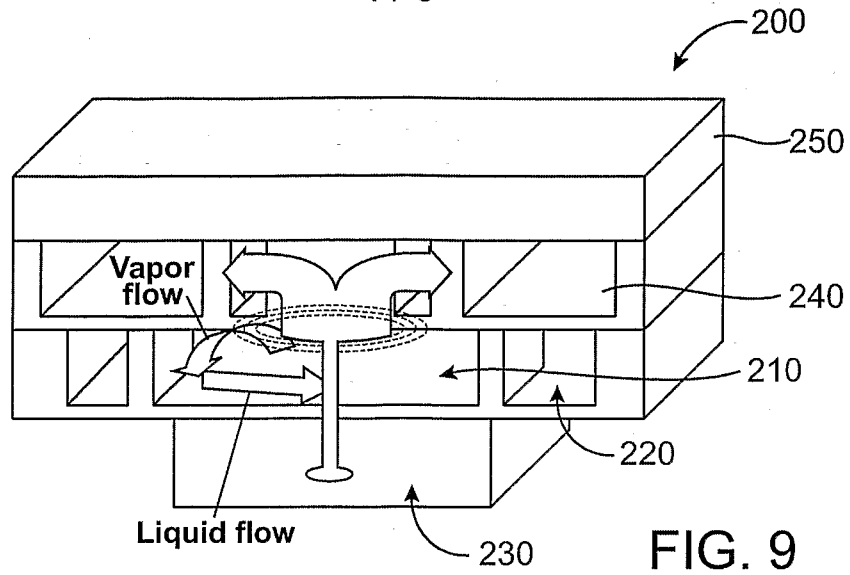
FIG. 2



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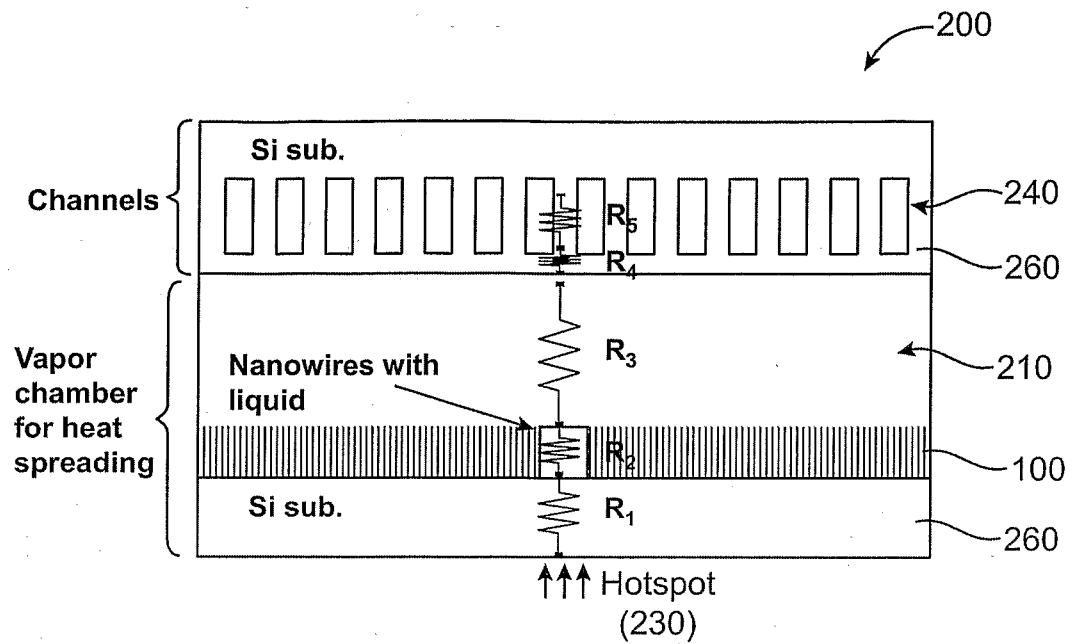


FIG. 12

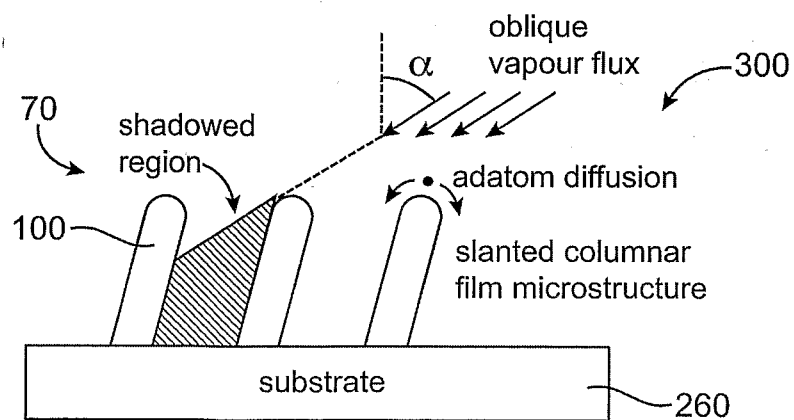


FIG. 13