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(54) **PASSIVE HEAT SINK FOR DYNAMIC THERMAL MANAGEMENT OF HOT SPOTS**

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H05K 7/20 (2006.01)

(52) **U.S. Cl.**
USPC **361/689**; 361/677; 361/705; 438/599; 257/707; 257/712

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CPC H01L 23/4093; H01L 23/4006; H01L 23/467; H01L 23/3672; H01L 23/427; H01L 23/473; H01L 2023/405; H01L 2924/14; H01L 2924/01079; F28F 3/12
USPC 361/676–678, 679.46–679.54, 361/688–722, 752, 760–761, 831
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,596,713 A * 8/1971 Katz 165/104.13
3,800,190 A * 3/1974 Marek 257/715
4,531,146 A * 7/1985 Cutchaw 257/713
4,612,978 A * 9/1986 Cutchaw 165/104.33
4,730,665 A * 3/1988 Cutchaw 165/80.4
4,823,863 A * 4/1989 Nakajima et al. 165/80.4
4,884,169 A * 11/1989 Cutchaw 361/700
5,131,233 A * 7/1992 Cray et al. 62/64
5,581,192 A * 12/1996 Shea et al. 324/722
5,768,103 A * 6/1998 Kobrinetz et al. 361/699
5,771,967 A * 6/1998 Hyman 165/274
5,854,092 A * 12/1998 Root et al. 438/106
5,943,211 A * 8/1999 Havey et al. 361/699
6,070,656 A * 6/2000 Dickey 165/104.26
6,120,130 A * 9/2000 Hirano et al. 347/46
6,349,760 B1 * 2/2002 Budelman 165/80.4
6,460,612 B1 * 10/2002 Sehmbey et al. 165/96

(Continued)

OTHER PUBLICATIONS

Darhuber, Anton A., et al., "Principles of Microfluidic Actuation by Modulation of Surface Stresses," Annual Review of Fluid Mechanics, vol. 37, Jan. 2005, pp. 425-455.

(Continued)

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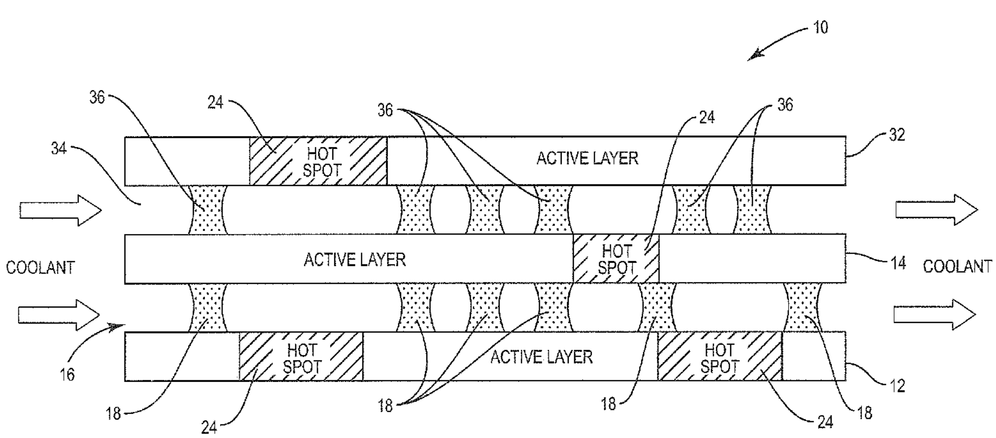
(57) **ABSTRACT**

A fully-passive, dynamically configurable directed cooling system for a microelectronic device is disclosed. In general, movable pins are suspended within a cooling plenum between an active layer and a second layer of the microelectronic device. In one embodiment, the second layer is another active layer of the microelectronic device. The movable pins are formed of a material that has a surface tension that decreases as temperature increases such that, in response to a temperature gradient on the surface of the active layer, the movable pins move by capillary flow in the directions of decreasing temperature. By moving in the direction of decreasing temperature, the movable pins move away from hot spots on the surface of the active layer, thereby opening a pathway for preferential flow of a coolant through the cooling plenum at a higher flow rate towards the hot spots.

35 Claims, 6 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

6,525,642	B1 *	2/2003	Kremers et al.	338/80
6,600,405	B1 *	7/2003	Kremers et al.	337/21
6,603,384	B1 *	8/2003	Kremers et al.	337/21
6,621,401	B1 *	9/2003	Kremers et al.	337/21
6,684,940	B1 *	2/2004	Chao et al.	165/104.21
6,827,134	B1 *	12/2004	Rightley et al.	165/104.26
6,889,755	B2 *	5/2005	Zuo et al.	165/104.26
6,955,062	B2 *	10/2005	Tilton et al.	62/259.2
6,955,063	B2 *	10/2005	Adiga et al.	62/259.2
7,362,574	B2 *	4/2008	Campbell et al.	361/699
7,450,381	B2 *	11/2008	Gilliland et al.	361/695
7,610,769	B2 *	11/2009	Tain et al.	62/259.2
7,626,483	B2 *	12/2009	Ohtsuka et al.	337/167
8,037,926	B2 *	10/2011	Martin et al.	165/80.4
8,051,905	B2 *	11/2011	Arik et al.	165/287
8,235,096	B1 *	8/2012	Mahefkey et al.	165/104.26
8,299,887	B2 *	10/2012	Ohtsuka et al.	337/167
2003/0048619	A1 *	3/2003	Kaler et al.	361/760
2005/0063875	A1 *	3/2005	Schatz et al.	422/100
2005/0135061	A1 *	6/2005	Kiley	361/700
2005/0135062	A1 *	6/2005	Kiley et al.	361/700
2005/0211427	A1 *	9/2005	Kenny et al.	165/299
2006/0134799	A1 *	6/2006	Sharma et al.	436/174
2006/0157223	A1 *	7/2006	Gelorme et al.	165/80.3
2007/0085054	A1 *	4/2007	Lin	252/70
2007/0119573	A1 *	5/2007	Mahalingam et al.	165/80.4
2008/0013281	A1 *	1/2008	Ouyang	361/707
2008/0043440	A1 *	2/2008	Fedorov	361/700
2008/0105829	A1 *	5/2008	Faris et al.	250/432 R
2008/0137316	A1 *	6/2008	Khaselev et al.	361/772
2008/0237843	A1 *	10/2008	Gupta et al.	257/713
2008/0266766	A1 *	10/2008	D'Urso et al.	361/681
2009/0040716	A1 *	2/2009	Fedorov	361/694
2009/0050294	A1 *	2/2009	Fedorov	165/80.3
2010/0254088	A1 *	10/2010	Ishida et al.	361/700
2010/0314093	A1 *	12/2010	Refai-Ahmed et al.	165/287
2012/0279068	A1 *	11/2012	Mahefkey et al.	29/890.032

OTHER PUBLICATIONS

Valentino, Joseph P., et al., "Thermocapillary actuation of liquids using patterned microheater arrays," Technical Digest, 12th International Conference on Solid State Sensors, Actuators and Microsystems, Jun. 8-12, 2003, pp. 667-669.

* cited by examiner

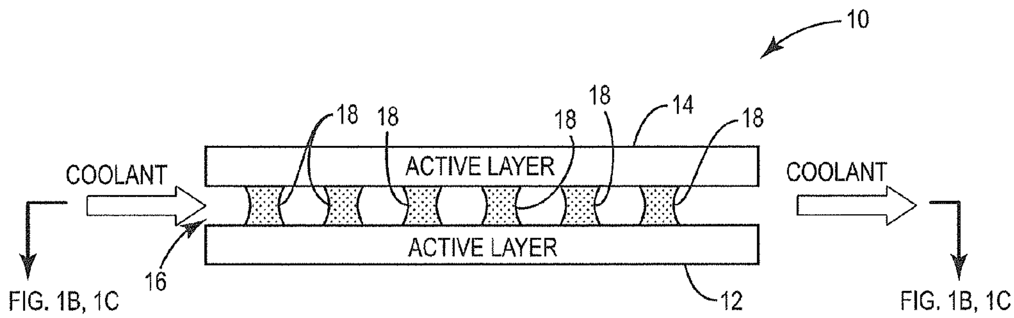

10
18
18
18
18
14
18
ACTIVE LAYER
COOLANT
COOLANT
ACTIVE LAYER
16
FIG. 1B, 1C
12
FIG. 1B, 1C

FIG. 1A

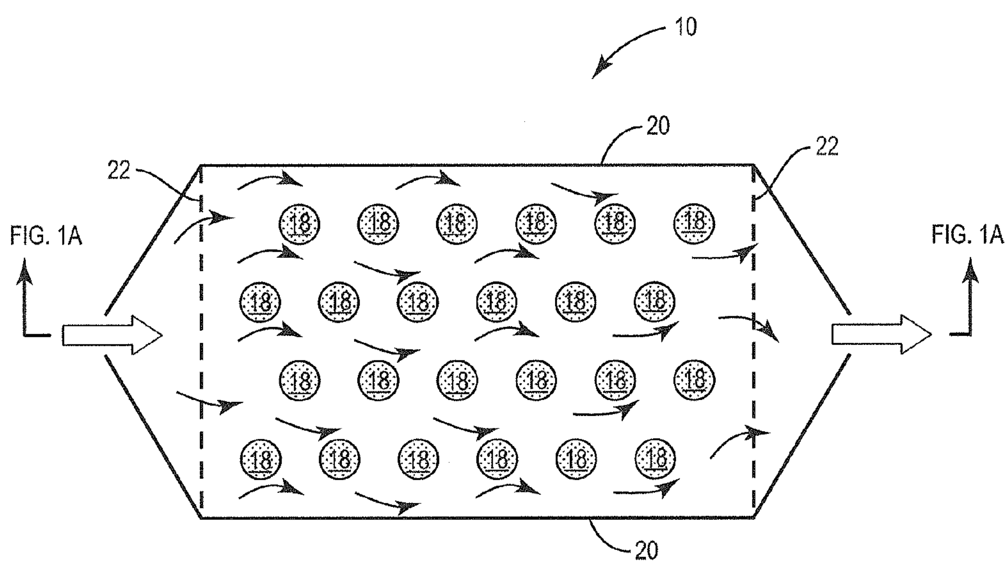

10
20
22
22
FIG. 1A
FIG. 1A
18
20

FIG. 1B

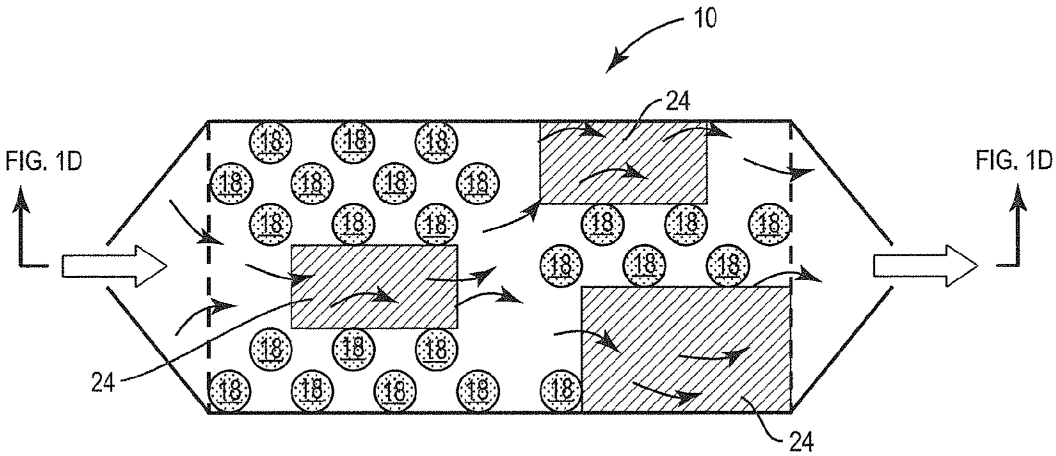

10
24
FIG. 1D
FIG. 1D
18
24
24

FIG. 1C

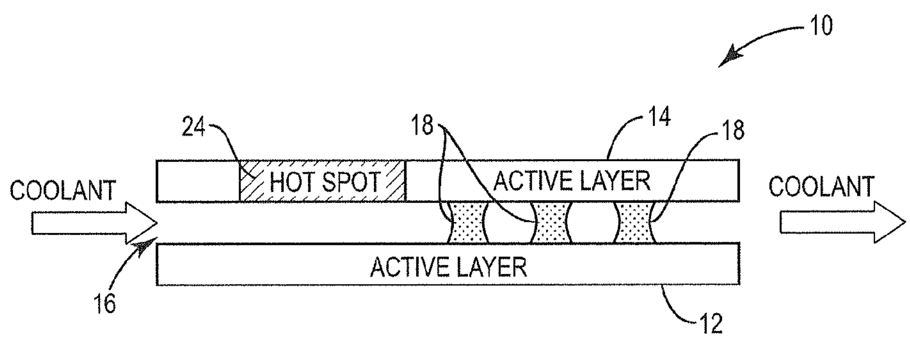

10
24
18
14
18
HOT SPOT
ACTIVE LAYER
COOLANT
COOLANT
ACTIVE LAYER
16
12

FIG. 1D

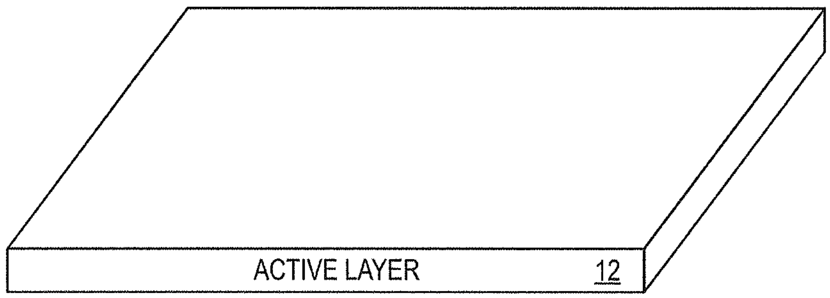


FIG. 2A

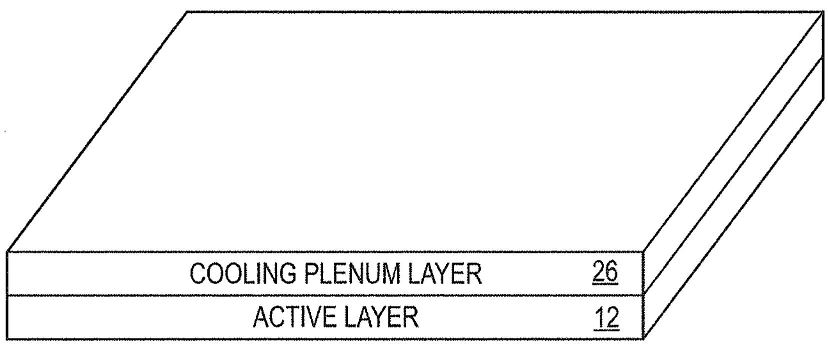


FIG. 2B

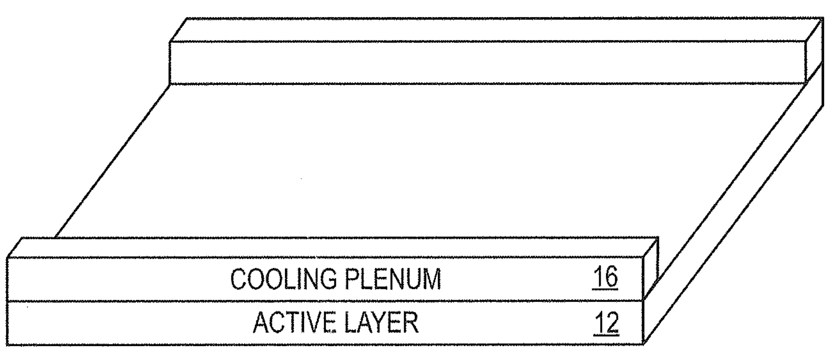


FIG. 2C

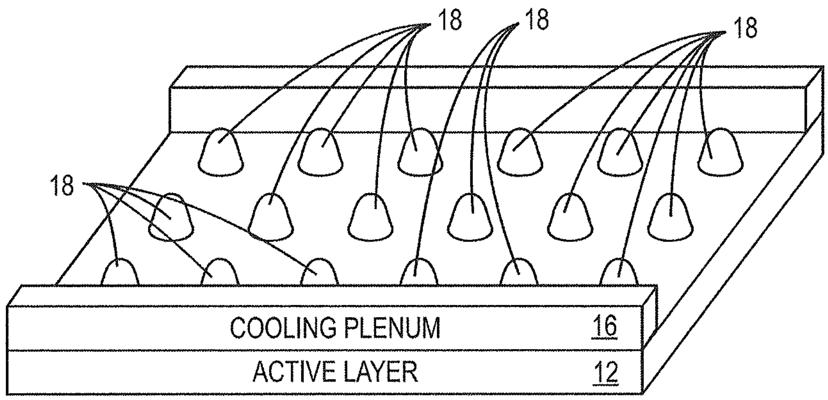

18
18
18
18
COOLING PLENUM 16
ACTIVE LAYER 12

FIG. 2D

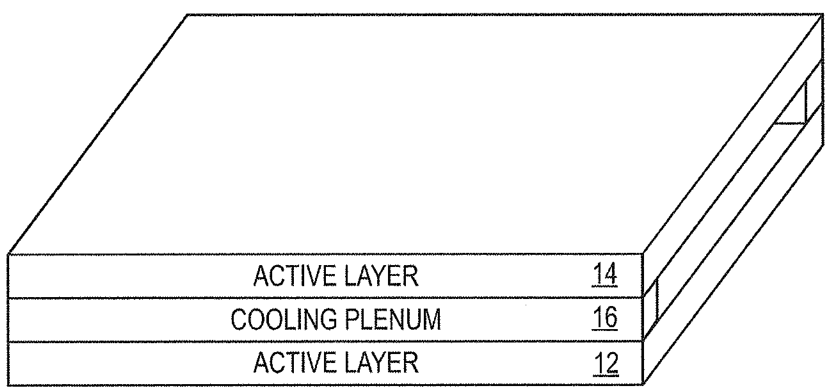

ACTIVE LAYER 14
COOLING PLENUM 16
ACTIVE LAYER 12

FIG. 2E

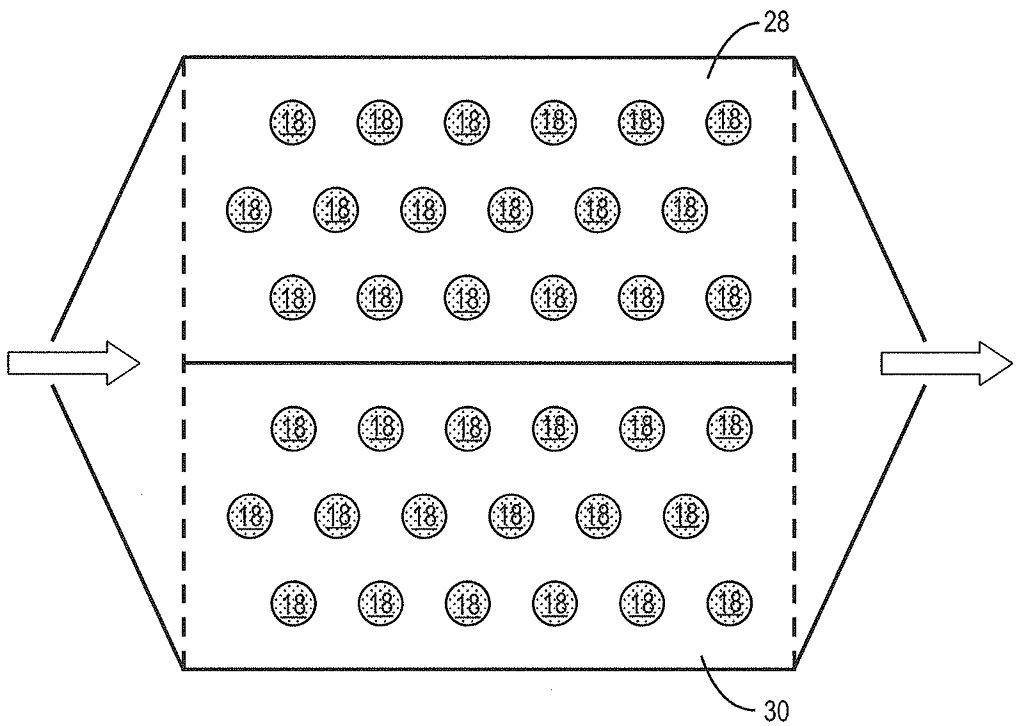


FIG. 3

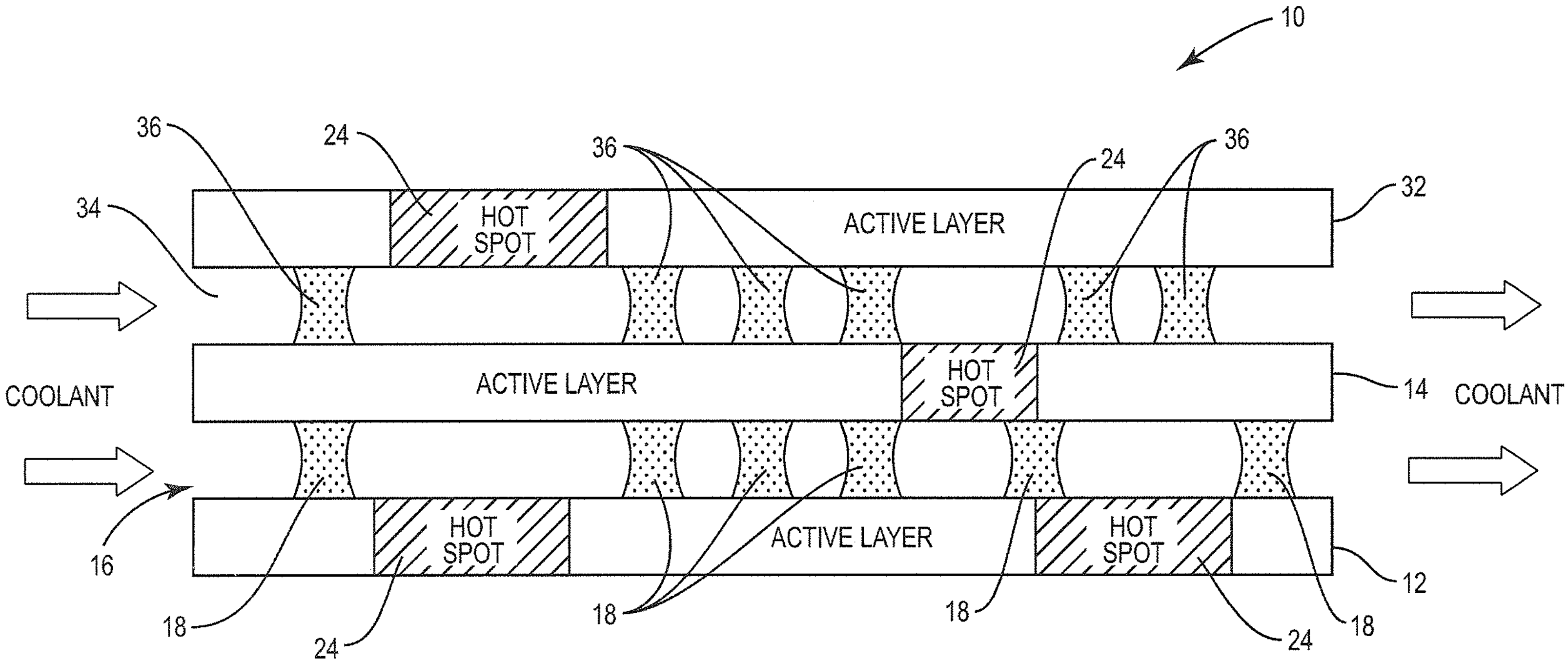

10
36
24
36
24
36
34
32
HOT SPOT
ACTIVE LAYER
ACTIVE LAYER
HOT SPOT
COOLANT
14
COOLANT
16
HOT SPOT
ACTIVE LAYER
HOT SPOT
12
18
24
18
18
24
18

FIG. 4

PASSIVE HEAT SINK FOR DYNAMIC THERMAL MANAGEMENT OF HOT SPOTS

RELATED APPLICATIONS

This application claims the benefit of provisional patent application Ser. No. 61/371,891, filed Aug. 9, 2010, the disclosure of which is hereby incorporated herein by reference in its entirety.

GOVERNMENTAL RIGHTS

This invention was made with government support under HR0011-10-3-0002 awarded by DARPA. The Government has certain rights in the invention.

FIELD OF THE DISCLOSURE

The present disclosure relates to a cooling system for a microelectronic device.

BACKGROUND

In the course of the past few years, the problem of removing heat resulting from the operation of microelectronic devices has elevated from being an important concern to becoming a widely recognized bottleneck limiting further progress of high performance microelectronic devices. Excessive heating affects not only performance, but also reliability. With continuing increase in integration levels and introduction of new 3-D chip and interconnect architectures, the challenge to cool microelectronic devices has become even more difficult.

As an example, traditional single core microprocessors generate a significant amount of heat, which is typically in the range of 20-50 Watts per square centimeter (W/cm^2). However, modern multi-core microprocessors result in significantly more heat. Multi-core microprocessors experience a global or uniform heat flux that is typically on the order of 20-50 W/cm^2. In addition, multi-core microprocessors experience hot spots resulting from the active cores that are typically in the range of 2 to 10 times greater than the global heat flux (i.e., as much as 500 to 1000 W/cm^2). Further compounding the issue, the number of cores that are active at any one time and the specific cores that are active at any one time dynamically changes. As a result of the activation and deactivation of the cores, the hot spots are dynamically moving. The heat issue in multi-core microprocessors is even further compounded by 3-D architectures that utilize stacks of multiple active layers (i.e., multiple layers of active cores).

The traditional approach to remove heat from microelectronic devices is not sufficient to alleviate the dynamically moving hot spots generated in multi-core microprocessors. For example, a traditional heat sink has to target the largest heat flux (i.e., worst case) produced at the hot spots and be able to dissipate such a large flux over the entire semiconductor die on which the microprocessor is formed. Thus, if the multi-core microprocessor is formed on a 1 cm^2 die with 10 layers and the worst case hot spot is 1000 W/cm^2, then the heat sink would be required to remove 10 kilowatts (kW) of heat (i.e., 1000 W/cm^2×10 layers×1 cm^2). This is not possible using conventional technology. As such, there is a need for a cooling system for microelectronic devices such as, but not limited to, multi-core microprocessors that have dynamically moving hot spots and, in some cases, multiple active layers.

SUMMARY

The present disclosure relates to a fully-passive, dynamically configurable directed cooling system for a microelectronic device. In general, movable pins are suspended within a cooling plenum between an active layer and a second layer of the microelectronic device. In one embodiment, the second layer is another active layer of the microelectronic device. The movable pins are formed of a material that has a surface tension that decreases as temperature increases. Due to the Marangoni effect, or capillary flow, the movable pins preferentially move in directions of increasing surface tension. Since the movable pins have a surface tension that decreases as temperature increases, the movable pins move in directions of decreasing temperature on the surface of the active layer.

By moving in the direction of decreasing temperature, the movable pins move to areas on the surface of the active layer that are cool (i.e., where the movable pins have the highest surface tension) and away from areas on the surface of the active layer that are hot (i.e., where the movable pins have the lowest surface tension). In this manner, the movable pins open a pathway for preferential flow of a coolant through the cooling plenum at a higher flow rate towards areas, or domains, of the active layer that need higher heat dissipation (i.e., hot spots) and bypassing the cool areas, or domains, that do not need cooling at a given instance of time. Further, in one embodiment, the hot spots in the active layers dynamically move over time. In response, the movable pins dynamically reconfigure in a fully passive manner, i.e., without use of any external means.

Those skilled in the art will appreciate the scope of the present disclosure and realize additional aspects thereof after reading the following detailed description of the preferred embodiments in association with the accompanying drawing figures.

BRIEF DESCRIPTION OF THE DRAWING FIGURES

The accompanying drawing figures incorporated in and forming a part of this specification illustrate several aspects of the disclosure, and together with the description serve to explain the principles of the disclosure.

FIGS. **1**A through **1**D illustrate a fully-passive, dynamically reconfigurable directed cooling system according to one embodiment of the present disclosure;

FIGS. **2**A through **2**E graphically illustrate a process for fabricating a microelectronic device including a fully-passive, dynamically reconfigurable directed cooling system according to one embodiment of the present disclosure;

FIG. **3** illustrates a multi-domain cooling plenum according to one embodiment of the present disclosure; and

FIG. **4** illustrates a microelectronic device having multiple stacked active layers and multiple cooling plenums according to one embodiment of the present disclosure.

DETAILED DESCRIPTION

The embodiments set forth below represent the necessary information to enable those skilled in the art to practice the embodiments and illustrate the best mode of practicing the embodiments. Upon reading the following description in light of the accompanying drawing figures, those skilled in the art will understand the concepts of the disclosure and will recognize applications of these concepts not particularly addressed herein. It should be understood that these concepts and applications fall within the scope of the disclosure and the accompanying claims.

FIGS. **1**A through **1**D illustrate a microelectronic device **10** including a fully-passive, dynamically configurable directed cooling system according to one embodiment of the present disclosure. As illustrated in FIG. **1**A, the microelectronic device **10** includes two active layers **12** and **14**, a cooling plenum **16** between the active layers **12** and **14**, and a number of droplets suspended within the cooling plenum **16** between the active layers **12** and **14** to form movable pins **18**. The active layers **12** and **14** are layers in which active components of the microelectronic device **10** are formed. For instance, in one embodiment, the microelectronic device **10** is a multi-core microprocessor, and each of the active layers **12** and **14** includes one or more cores of the multi-core microprocessor. A coolant flows through the cooling plenum **16** and is directed by the movable pins **18**. The coolant may be any desired coolant that is suitable for flowing through the cooling plenum **16**. For instance, the coolant may be air or water, but is not limited thereto. As discussed below, the movable pins **18** move within the cooling plenum **16** in such a manner that the coolant is directed to areas of the active layers **12** and **14** that need cooling, which are referred to herein as hot spots.

In one embodiment, the movable pins **18** are liquid droplets formed of a liquid material having a high thermal conductivity and a surface tension that decreases with temperature (i.e., a negative surface tension temperature coefficient). As discussed below in detail, some exemplary liquid materials that may be used to form the movable pins **18** are: Gallium or Gallium-based Indium-Tin (InPb) alloys, surfactant-stabilized deionized (DI) water, other Gallium-based alloys doped with Indium and Tin (e.g., commercially-manufactured Galinstan alloy with composition 68.5% Ga21.5% In10% Sn), or low-melting temperature solders which can be doped with Gallium. In another embodiment, the movable pins **18** are droplets formed of a composite material including a solid core surrounded by a liquid shell. Preferably, the solid core is material having high thermal conductivity, and the liquid shell is a liquid material having a surface tension that decreases with temperature (i.e., a negative surface tension temperature coefficient). Some exemplary non-limiting materials that may be used for the solid core are Copper, Silver, Aluminum, and Carbon Nanotube (CNT) bundles/diamonds.

In one embodiment, as used herein, a material having a "high thermal conductivity" is a material having a thermal conductivity in a range of or including 1 to 2000 Watts per meters-Kelvin (W/mK). In another embodiment, a material having a "high thermal conductivity" is a material having a thermal conductivity in a range of and including 10 to 500 W/mK. Further, in one embodiment, the surface tension temperature coefficient of the material of which the movable pins **18** are formed is in a range of and including approximately −0.7 to −0.01 milli-Newtons per meters-Kelvin (mN/mK) (or even lower). In another embodiment, the surface tension temperature coefficient of the material of which the movable pins **18** are formed is in a range of and including approximately −0.7 to −0.1 mN/mK. Note that the ranges for high thermal conductivity and negative surface tension temperature coefficient given above are exemplary and are not intended to limit the scope of the present disclosure.

A density of material used to form the movable pins **18** is preferably approximately equal to or greater than the density of the coolant. For example, if the coolant is air with the density of ~1 kilogram per cubic meter (kg/m^3), then the density of the material used to form the movable pins **18** is, in one embodiment, at least 2 or 3 times that of air or, in another embodiment, in a range of 1 to 10 kg/m^3. If the coolant is water with a density of ~1000 kg/m3, then the density of the material used to form the movable pins **18** is, in one embodiment, 2 to 3 times greater than that of water (i.e., approximately 2000 to 3000 kg/m^3). Essentially, the density of the material used to form the movable pins **18** is a trade-off between response time (i.e., how quickly and easily the movable pins **18** will move in response to the temperature gradient by capillary forces due to less inertia) and having sufficient density to not be swept away by the coolant.

By utilizing the Marangoni effect, the movable pins **18** preferentially move within the cooling plenum **16** in directions of increasing surface tension, where surface tension is a function of temperature. Since the movable pins **18** have a surface tension that decreases as temperature increases, due to the Marangoni effect, the movable pins **18** move to areas on the surfaces of the active layers **12** and **14** that are cool (i.e., where the movable pins **18** have the highest surface tension) and away from areas on the surfaces of the active layers **12** and **14** that are hot (i.e., where the movable pins **18** have the lowest surface tension). The movement of the movable pins **18** according to the Marangoni effect is also referred to herein as capillary flow. In this manner, the movable pins **18** open a pathway for preferential flow of the coolant through the cooling plenum **16** at a higher flow rate towards areas, or domains, of the active layers **12** and **14** that need higher heat dissipation, which are referred to herein as hot spots, and bypassing the cool areas, or domains, of the active layers **12** and **14** that do not need cooling at a given instance of time. Further, in one embodiment, the hot spots in the active layers **12** and **14** dynamically move over time. In response, the movable pins **18** dynamically reconfigure in a fully passive manner.

Notably, the movable pins **18** are formed such that they do not coalesce. More specifically, in one embodiment, a surfactant is used to prevent the droplets forming the movable pins **18** from coalescing. In another embodiment, the droplets forming the movable pins **18** are electrically charged of the same sign (e.g., all positively charged). Because they are electrically charged of the same sign, the movable pins **18** repel one another, which prevents the movable pins **18** from coalescing.

FIG. **1**B is a top down view of the microelectronic device **10** of FIG. **1**A showing the movable pins **18** within the cooling plenum **16**. In FIG. **1**B, the movable pins **18** are illustrated as being uniformly distributed within the cooling plenum **16**. This occurs when a uniform temperature is present across the surfaces of the active layers **12** and **14**. As a result, coolant flowing through the cooling plenum **16** provides uniform heat dissipation over the entire surfaces of the active layers **12** and **14**. FIG. **1**B also illustrates walls **20** of the cooling plenum **16** and a mesh **22** at openings in the cooling plenum **16** through which the coolant flows. The walls **20** and the mesh **22** confine the movable pins **18** to the cooling plenum **16**. Notably, openings in the mesh **22** are sized such that they are large enough to allow coolant (e.g., air or water) to flow through the mesh **22** into and out of the cooling plenum **16** but small enough to confine the movable pins **18** inside the cooling plenum **16**. The exact sizing of the openings in the mesh **22** depends on the particular embodiment (e.g., the size of the droplets forming the movable pins **18**, the type of coolant used, etc.). Further, in the embodiment where the movable pins **18** are electrically charged, the mesh **22** may also be electrically charged of the same sign.

The size of the movable pins **18** is, in one embodiment, on the order of magnitude of a typical hot spot. In the case of a multi-core microprocessor, the size of the movable pins **18** may be as large as a core of the multi-core microprocessor. In one particular embodiment, the size, or diameter, of each of the movable pins **18** is in a range of and including 100 nanometers (nm) to 1 millimeter (mm). In another embodiment, the size, or diameter, of each of the movable pins **18** is in a range of and including 10 to 100 micrometer (μm). Note, however, that these sizes are exemplary and are not intended to limit the scope of the present disclosure. Further, the particular size of the movable pins **18** used for a particular application may be decided based on a trade-off between the flexibility of the cooling system resulting from the use of a larger number of smaller movable pins **18** (e.g., the smaller the movable pins **18** are, then the more movable pins **18** that can be put in the cooling plenum **16**, which in turn increases the number of optimum pin configurations that can be attained with a faster response time) and the reduced complexity and cost resulting from using a smaller number of larger movable pins **18**. Also, when uniformly distributed as shown in FIG. **1**B, the spacing between the movable pins **18** (i.e., the lateral distance between the movable pins **18**) is, in one embodiment, in a range of and including 1 to 100 μm. However, the present disclosure is not limited thereto. The lateral distance between the movable pins **18** when uniformly distributed may vary depending on the particular application.

Gallium added in quantities up to 2% in common solders aids significantly in their wetting and flow characteristics. In another embodiment, the movable pins **18** are droplets of a composite material where each of the movable pins **18** includes a solid core of a material having a high thermal conductivity (e.g., Copper, Silver, Aluminum, and CNT bundles/diamonds) and a liquid shell surrounding the solid core of a liquid material having a surface tension that decreases with increasing temperature. Relevant properties of three representative materials are summarized in Table 1, and are used below to describe performance characteristics of the disclosed cooling system. Note, however, as will be appreciated by one of ordinary skill in the art upon reading this disclosure, the materials discussed herein for the movable pins **18** are exemplary. Other types of liquid or composite materials having high thermal conductivity and a surface tension that decreases as temperature increases may be used.

TABLE 1

Relevant properties of exemplary substances for movable pins

	Melting Point (° C. at 1 atm)	Boiling Point (° C. at 1 atm)	Density (kg/m^3 at 20° C.)	Viscosity (Pa * s at 20° C.)	Thermal Conductivity (W/mK at 20° C.)	Surface Tension (mN/m as f (T in ° C.))
Gallium	29.8	2204	6095 (at MP)	~0.002 (at MP)	40	~708 − 0.66 * (T − 29.8)
Galinstan Alloy (68.5%Ga21.5%In10%Sn)	−19	>1300	6440	0.0024	16.5	~718 − 0.66 * (T − 29.8)
Water (for comparison)	0	100	1000	0.001	0.609	75 − 0.17 * T

FIG. **1**C is a top down view of the microelectronic device **10** of FIG. **1**A illustrating the dynamic re-configuration of the movable pins **18** in response to hot spots **24** in the active layers **12** and **14**. Specifically, the hot spots **24** create a temperature gradient over the surfaces of the active layers **12** and **14**. This temperature gradient induces movement of the movable pins **18** in directions of decreasing temperature. As a result, as shown in FIG. **1**C, the movable pins **18** migrate to cool areas on the surfaces of the active layers **12** and **14** away from the hot spots **24**. This opens a pathway for preferential flow of the coolant within the cooling plenum **16** at a higher flow rate towards the hot spots **24** and bypassing the cooler areas. Notably, as the hot spots **24** move, so too do the movable pins **18**. FIG. **1**D is a cross-sectional view of FIG. **1**C showing the large opening created by the movable pins **18** for one of the hot spots **24** to direct the coolant to the hot spot **24**.

In one embodiment, the movable pins **18** are liquid droplets of Gallium or Gallium-based InPb alloys, in which case the coolant may be, for example, air or water. In another embodiment, the movable pins **18** are liquid droplets of surfactant-stabilized DI water, in which case the coolant may be, for example, air. Some other liquid substances that may be used for the movable pins **18** include, but are not limited to: (i) other Gallium-based alloys doped with Indium and Tin that can be used to tune the melting point, viscosity, thermal conductivity, and surface tension (e.g., commercially-manufactured Galinstan alloy with composition 68.5% Ga21.5% In10% Sn); and (ii) low-melting temperature solders which can be doped with Gallium to modify their properties towards greater substrate wettability with strong temperature dependence of the surface tension and improved fluidity. In fact,

High surface wettability (i.e., contact angle approaching zero) of the material used for the movable pins **18** to the surfaces of the active layers **12** and **14** is one desired property. Preferably, the wettability is such that a contact angle between the movable pins **18** and the surfaces of the active layers **12** and **14** is between 0 and 90 degrees. High surface wettability increases a contact area between the movable pins **18** and the surfaces of the active layers **12** and **14**, thereby providing high capillary coupling between the movable pins **18** and the active layers **12** and **14**. The high capillary coupling supports significant capillary or interfacial forces to the movable pins **18** resulting in fast movement of the movable pins **18** in response to a temperature gradient.

Gallium and Gallium-based alloys are highly wettable (i.e., have a contact angle approaching zero) to most substrate materials, including Silicon dioxide (SiO_2) which is commonly used as a dielectric passivation layer for electrical insulation between the active layers (e.g., the active layers **12** and **14**) in the stacked-die forming the microelectronic device **10**. Silicon dioxide is also wettable by water with the contact angle between 0 and 90°, depending on the oxide thickness. This means that the capillary coupling between the movable pins **18** when made of either Ga/Ga-based alloys or water and the SiO_2 substrate will be strong to support application of significant capillary forces to the movable pins **18** resulting in their fast motion in response to the temperature gradient.

It should be noted that at near-room temperatures (in the range of expected application of electronic components) Gallium and Gallium-based InPb-alloys (e.g., Galinstan) are neither toxic nor reactive towards air and water due to the formation of a passive, protective oxide layer. Further, Gallium and its InPb-doped alloys are insoluble in water or organic solvents. Therefore, a wide range of fluids, including water, organic liquids, and air could be used as coolants in conjunction with the movable pins **18** when formed of Gallium or Gallium-alloy liquid droplets. It should also be noted that Galinstan and other Gallium and Gallium-based InPb-alloys are commercially available materials.

The speed of the capillary motion (i.e., the speed of the movement of the movable pins **18**) corresponds to the response time of the cooling system described herein. The speed of the capillary motion is proportional to the temperature coefficient in the surface tension temperature-dependence $\partial\gamma/\partial T$ (see Table 1), the magnitude of the temperature gradient ∇T driving capillary flow in the direction of increased surface tension (i.e., towards lower temperatures for liquids with a negative surface tension temperature coefficient), the vertical height h of the movable pins **18** defined by a gap size of the cooling plenum **16** (i.e., a distance between the active layers **12** and **14**), and inversely proportional to the liquid viscosity μ. For the capillary motion of liquid films, which can be used as an approximation for the movable pins **18**, an experimentally-verified expression exists to predict the speed of capillary motion: $V \approx 0.5 \times h \times \partial\gamma/\partial T \times \nabla T \times \mu^{-1}$. Note that this expression is for a liquid in contact at one side only with a substrate, and the velocity would double for the movable pins **18** which are confined between and interacting with two substrates of the cooling plenum **16** (i.e., the two active layers **12** and **14**).

For example, if the cooling plenum **16** has a thickness of 100 μm and a temperature gradient of 10^5 degrees Celsius per meter (° C./m) (corresponding to 10° C. temperature drop across the 100 μm distance, which is quite typical for hot spots) is imposed within the cooling plenum **16**, the resulting motion of the movable pins **18** would occur at approximately 2.8 meters per second (m/s) if the movable pins **18** are formed of Galinstan and approximately 1.7 m/s if the movable pins **18** are formed of water. This translates into a response time for rearrangement of the movable pins **18** (i.e., time to move the movable pins **18** to new positions from the hot to the cold zone on the substrate, ~distance/velocity) of approximately 0.03 milliseconds for Galinstan and approximately 0.06 milliseconds for water. While this analysis does not account for intra-droplet interactions due to collective motion and inertial effects (proportional to the material density of the material used for the movable pins **18**), these effects are expected to have minimal impact due to a very small size of the movable pins **18** and therefore strong dominance of surface-vs-bulk transport processes. Thus, this analysis provides a good first-order approximation for the transient response of the disclosed cooling system, which is impressive and responsive to expected dynamics of hot spot migration (~sub-millisecond) in microprocessors. It should be noted that if the temperature gradient is increased by an order of magnitude, the capillary velocities would increase by the same order of magnitude, while the time response of the cooling scheme (re-arrangement of the movable pins **18**) would decrease by two orders of magnitude, leading to an unprecedented sub-microsecond response of the cooling system.

FIGS. **2**A through **2**E graphically illustrate a process for forming the microelectronic device **10** of FIGS. **1**A through **1**D according to one embodiment of the present disclosure. As illustrated in FIG. **2**A, the process begins with the active layer **12**. Then, as illustrated in FIG. **2**B, a cooling plenum layer **26** is provided on the active layer **12**. The cooling plenum layer **26** may be formed of any suitable material such as, for example, a dielectric or insulation material such as, for example, SiO_2, a polymer, or the like. Next, the cooling plenum layer **26** is etched or otherwise processed to form the cooling plenum **16**, as illustrated in FIG. **2**C. The liquid droplets, or movable pins **18**, are then provided in the cooling plenum **16**, as illustrated in FIG. **2**D. Notably, the manner in which the liquid droplets are formed and deposited is well known in the art. Any conventional technique may be used, including ultrasonic or electrostatic dispersion, ink-jet printing, and others. Lastly, the active layer **14** is provided over the cooling plenum **16**, as illustrated in FIG. **2**E. As this point, the liquid droplets are suspended between the two active layers **12** and **14** as the movable pins **18**. While not shown, the mesh **22** is provided over the openings at each end of the cooling plenum **16** (see FIGS. **1**B and **1**C).

FIG. **3** illustrates another embodiment of the cooling plenum **16**. In this embodiment, the cooling plenum **16** includes multiple domains, or sectors, **28** and **30**. Note that while two domains are illustrated, the cooling plenum **16** may include any number of one or more domains. Further, the domains may be of different sizes and/or shapes. Each of the domains **28** and **30** includes movable pins **18**. The movable pins **18** in the domain **28** are constrained to the domain **28**. Likewise, the movable pins **18** in the domain **30** are constrained to the domain **30**. As discussed above, the movable pins **18** move away from hot spots to provide directed flow of the coolant to the hot spots. Size, number, and material of the movable pins **18** in the domains **28** and **30** may be different depending on specific cooling requirements of each of the domains **28** and **30**.

FIG. **4** illustrates another embodiment of the microelectronic device **10** where the microelectronic device **10** includes multiple active layers and cooling plenums. Specifically, in this embodiment, the microelectronic device **10** includes the active layers **12** and **14** as well as an additional active layer **32**. The microelectronic device **10** includes the cooling plenum **16** between the active layers **12** and **14** and another cooling plenum **34** between the active layers **14** and **32**. The cooling plenum **34** includes droplets suspended between the active layers **14** and **32** that form movable pins **36** in the same manner described above with respect to the movable pins **18**. In this manner, the cooling system described herein may be extended to microelectronic devices having any number of stacked layers.

It should be noted that while the cooling plenum (e.g., the cooling plenum **16**) and movable pins (e.g., the movable pins **18**) are described herein as being implemented between two active layers (e.g., the active layers **12** and **14**), the present disclosure is not limited thereto. For example, a cooling plenum may be provided between an active layer and a non-active layer (e.g., an SiO_2 layer). As another example, a single active layer may be between two cooling plenums (e.g., a cooling plenum and a non-active layer on both the top and bottom surfaces of the single active layer).

Some exemplary and non-limiting benefits of the cooling system described herein are as follows. The cooling system is fully passive and dynamically reconfigurable (i.e., adaptive). As the hot spots on the surfaces of the active layers **12** and **14** (and **32**) move due to, for example, activation and deactivation of the cores of a multi-core microprocessor, the movable pins **18** (and **36**) re-configure to direct coolant flow to the hot spots. This is done in a fully-passive manner without the need for any active control system, which in turn reduces packaging complexity and cost and improves reliability. Further, the cooling system described herein is universal and can work with different coolants ranging from air to liquids depending on the specific power dissipation profile of a given application of a microelectronic device. Also, the form factor of the cooling system which is composed of a small-gap cooling plenum confining movable pins is fully compatible with architectural features of a 3-D stacked die, thus providing the possibility of a chip-level "drop-in" solution for any number of active layers, possibly on an as-needed basis depending on a specific power profile for each active layer. Lastly, the cooling system minimizes power consumption (cooling overhead) as coolant is not pumped over the cool areas of the active layers such that only the hot spots are cooled.

Those skilled in the art will recognize improvements and modifications to the preferred embodiments of the present disclosure. All such improvements and modifications are considered within the scope of the concepts disclosed herein and the claims that follow.

What is claimed is:

1. A microelectronic device comprising:

an active layer;

a cooling plenum on a surface of the active layer;

a second layer on the cooling plenum opposite the active layer such that the cooling plenum is between the active layer and the second layer; and

a plurality of movable pins suspended in the cooling plenum between the active layer and the second layer, the plurality of movable pins being formed of a material having a surface tension that decreases as temperature increases such that, in response to a temperature gradient on the surface of the active layer, the plurality of movable pins move by capillary flow in directions of decreasing temperature on the surface of the active layer.

2. The microelectronic device of claim **1** wherein the plurality of movable pins move away from one or more hot spots on the surface of the active layer.

3. The microelectronic device of claim **1** wherein the plurality of movable pins direct flow of a coolant through the cooling plenum to one or more hot spots on the surface of the active layer.

4. The microelectronic device of claim **1** wherein movement of the plurality of movable pins is fully passive.

5. The microelectronic device of claim **1** wherein the plurality of movable pins are dynamically re-configurable in response to changes in the temperature gradient on the surface of the active layer.

6. The microelectronic device of claim **1** wherein the material of which the plurality of movable pins are formed has a negative surface tension temperature coefficient.

7. The microelectronic device of claim **6** wherein the negative surface tension temperature coefficient is in a range of and including −0.7 mN/mK to −0.01 mN/mK.

8. The microelectronic device of claim **6** wherein the negative surface tension temperature coefficient is in a range of and including −0.7 mN/mK to −0.1 mN/mK.

9. The microelectronic device of claim **1** wherein the material of which the plurality of movable pins are formed has a high thermal conductivity.

10. The microelectronic device of claim **9** wherein the high thermal conductivity is in a range of and including 1 to 2000 W/mK.

11. The microelectronic device of claim **9** wherein the high thermal conductivity is in a range of and including 10 to 500 W/mK.

12. The microelectronic device of claim **1** wherein a contact angle between each of the plurality of movable pins and the surface of the active layer is in a range of 0 to 90 degrees.

13. The microelectronic device of claim **1** wherein the plurality of movable pins have a sub-millisecond response time to changes in the temperature gradient on the surface of the active layer.

14. The microelectronic device of claim **1** wherein the plurality of movable pins is a plurality of liquid droplets formed of a liquid material having a surface tension that decreases as temperature increases such that, in response to the temperature gradient on the surface of the active layer, the plurality of movable pins move by capillary flow in directions of decreasing temperature on the surface of the active layer.

15. The microelectronic device of claim **14** wherein the liquid material is gallium.

16. The microelectronic device of claim **14** wherein the liquid material is a gallium based indium-tin (InPb) alloy.

17. The microelectronic device of claim **14** wherein the liquid material is gallium based alloy doped with indium and tin.

18. The microelectronic device of claim **14** wherein the liquid material is galinstan.

19. The microelectronic device of claim **14** wherein the liquid material is water.

20. The microelectronic device of claim **14** wherein the liquid material is surfactant-stabilized deionized (DI) water.

21. The microelectronic device of claim **14** wherein the liquid material is solder with up to 2% gallium.

22. The microelectronic device of claim **1** wherein the plurality of movable pins is a plurality of droplets of a composite material such that each of the plurality of movable pins has a solid core and a liquid shell surrounding the solid core, the liquid shell being formed of a liquid material having a surface tension that decreases as temperature increases such that, in response to the temperature gradient on the surface of the active layer, the plurality of movable pins move by capillary flow in directions of decreasing temperature on the surface of the active layer.

23. The microelectronic device of claim **22** wherein the solid core is formed of a material having a high thermal conductivity.

24. The microelectronic device of claim **23** wherein the high thermal conductivity is in a range of and including 1 to 2000 W/mK.

25. The microelectronic device of claim **23** wherein the high thermal conductivity is in a range of and including 10 to 500 W/mK.

26. The microelectronic device of claim **23** wherein the liquid shell surrounding the solid core provides a contact angle with the surface of the active layer in a range of and including 0 to 90 degrees.

27. The microelectronic device of claim **1** wherein a surfactant is utilized to prevent the plurality of movable pins from coalescing.

28. The microelectronic device of claim **1** wherein the plurality of movable pins are electrically charged of a same sign.

29. The microelectronic device of claim **1** wherein a density of the material of which the plurality of movable pins are formed is approximately equal to or greater than a density of a coolant that flows through the cooling plenum.

30. The microelectronic device of claim **1** wherein, when a uniform temperature is provided across the surface of the active layer, a lateral distance between the plurality of movable pins is in a range of and including 1 to 100 micrometers.

31. The microelectronic device of claim **1** wherein each of the plurality of movable pins has a diameter in a range of and including 100 nanometers to 1 millimeter.

32. The microelectronic device of claim **1** wherein each of the plurality of movable pins has a diameter in a range of and including 10 to 100 micrometers.

33. The microelectronic device of claim **1** wherein the second layer is a second active layer.

34. The microelectronic device of claim **1** wherein the cooling plenum comprises a plurality of domains.

35. The microelectronic device of claim **1** further comprising:

a plurality of active layers, including the active layer and the second layer, that are stacked; and

a plurality of cooling plenums including the cooling plenum, each cooling plenum of the plurality of cooling plenums being between a corresponding pair of the plurality of active layers; and

for each cooling plenum of the plurality of cooling plenums, a plurality of movable pins suspended in the cooling plenum between the corresponding pair of the plurality of active layers, the plurality of movable pins being formed of a material having a surface tension that decreases as temperature increases such that, in response to a temperature gradient on corresponding surfaces of the corresponding pair of the plurality of active layers, the plurality of movable pins move by capillary flow in directions of decreasing temperature on the corresponding surfaces of the corresponding pair of the plurality of active layers.

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