

SPRAY COOLING SYSTEM

BACKGROUND OF THE INVENTION

This invention relates generally to cooling systems for heat-generating devices and, more particularly, to a spray cooling system and a method of using the spray cooling system to cool a heat source.

With the advent of semiconductor devices having increasingly large component densities, the removal of heat generated by the devices has become an increasingly challenging technical issue. Furthermore, typical processor boards can, in some instances, include multiple CPU modules, application-specific integrated circuits (ICs), and static random access memory (SRAM), as well as a dc-dc converter. Heat sinks can be used to increase the heat-dissipating surface area of such devices. However, heat sinks, and their interfaces to the cooled devices, can provide interference in the heat flow, and can lead to uneven cooling.

Known cooling methods for semiconductors include free-flowing and forced-air convection, free-flowing and forced-liquid convection, pool boiling (i.e., boiling a liquid cooling fluid off of a submerged device), and spray cooling (i.e., boiling a liquid cooling fluid off of a device being sprayed with the liquid). Because liquids typically have a high latent heat of vaporization, these latter two methods provide for a high heat-transfer efficiency, absorbing a large quantity of heat at a constant temperature. Typically, the cooling fluid used has a relatively low boiling point (the temperature to maintain) and is inert to the heat source. For semiconductor devices, FED. CIR.-72, i.e., Fluorinert®, sold by 3M Corporation, is one of a number of known suitable cooling liquids.

The use of these boiling/vaporizing methods is limited to a maximum power density, the critical heat flux (CHF). At higher densities, the vaporized cooling fluid forms a vapor barrier insulating the device from the liquid cooling fluid, thus allowing the wall temperature of the device to increase greatly. This phenomenon is referred to as pooling. When a coolant is properly sprayed, it can disperse such a vapor layer, and its CHF can be well over an order of magnitude higher than the CHF of a pool boiling system. This high CHF is reliant on having a uniform spray. Thus, spray cooling presently provides the most efficient cooling for a heat-generating device, such as a semiconductor device.

Typically, current sprayer designs employ either pressurized liquid spraying or pressurized gas atomizing. A number of factors affect the performance of spray cooling, thus affecting the heat transfer coefficient h and/or the CHF. It is commonly understood that surface roughness and wettability of the sprayed component are two of these factors, and the orientation of the surface being sprayed can be a third. In particular, it is believed that h is higher for rough surfaces when using a pressurized liquid spray, and for smooth surfaces when using gas atomizing. Surfaces with decreased wettability appear to have a marginal increase in h .

Critical to consistent, controlled cooling is the controlled application of the liquid cooling fluid in a desired distribution, flow rate, and velocity. For example, at a low mass flow rate, CHF and h increase with the mass flow rate. However, at a critical mass flow rate, the advantages of increased mass flow are diminished due to pooling and/or due to a transition to single phase heat transfer. Thus, a spray cooling system is preferably operated uniformly at a mass flow rate defined at a point before the critical mass flow rate is reached. All of these factors make critical the design of the sprayer, i.e., the design of the nozzle and its related spray devices.

Also important to the cooling system design is its operating temperature. In particular, it is desirable to configure the system to operate at a high h , which will occur with a design temperature above the boiling temperature and below a temperature that will dry out the sprayed coolant. The amount of heat to be dissipated must be less than the CHF.

For pressure-assisted spraying, consistent, controlled spraying requires one or more high pressure pumps that provide a precise pressure to pump the liquid through a nozzle, even at varying flow rates. Both the distribution and the flow rate of the sprayed liquid can change with variations in the driving pressure and/or small variations in the nozzle construction. Thus, the cooling system is a sensitive and potentially expensive device that can be a challenge to control.

For gas atomizing, consistent, controlled spraying requires a pressurized gas that is delivered to a sprayhead design in a precise manner. Because the gas must be pressurized separately from the cooling fluid, such systems are not typically closed systems. The gas must be bled out for the condenser to run efficiently. Furthermore, both the distribution and the flow rate of the cooling fluid can change with variations in the gas pressure. Thus, the cooling system is a sensitive and potentially expensive device that can be a challenge to control.

Accordingly, there has existed a need for an accurate, reliable and cost-efficient spray cooling system. The present invention satisfies these and other needs, and provides further related advantages.

SUMMARY OF THE INVENTION

The present invention provides a spray cooling system for cooling a heat source, embodiments of which can exhibit improved accuracy, reliability and/or cost efficiency. Embodiments of the invention typically feature an incremental sprayer configured to eject an incremental amount of the cooling fluid on the heat source. The cooling fluid is sprayed in response to a control signal, which is sent to the sprayer by a controller.

Advantageously, these features provide for accurate delivery of cooling fluid at precise and controllable rates. The technology for this type of incremental sprayer is well developed in the ink-jet printer arts, and it is relatively inexpensive to manufacture. Furthermore, the design can be modular, offering quickly and easily replaceable units.

The invention further features the use of thermal ink-jet technology in designing the sprayer. In particular, the embodiment of the invention may have a body defining a chamber configured to hold a volume of the cooling fluid, and defining an orifice in communication with the chamber. A heating element is in thermal communication with the chamber, and is configured to vaporize a portion of the cooling fluid held within the chamber. The orifice is configured to direct cooling fluid from the chamber to the heat source upon the heating element vaporizing a portion of the cooling fluid held within the chamber.

This technology generally provides for efficient delivery of the cooling fluid to the heat source. Some known inert cooling fluids have viscosities and boiling points similar to that of ink-jet ink, and the ink-jet sprayers are typically adaptable to use with the cooling fluids. Furthermore, unlike typical ink-jet ink, cooling fluid does

not contain particulate matter that can clog the system. Thus, the system is both reliable and cost efficient to design.

5 The invention further features the ejection of incremental amounts of a cooling fluid on the heat source, using an incremental sprayer, spaced over a number of time increments. Either the incremental time or the amount ejected can be varied to adjust the flow rate to an optimal level. The system can be controlled by monitoring, either directly or indirectly, the temperature of the heat source and the amount of pooling or dry-out that is occurring, if any. This can provide for optimized cooling of a heat source.

10 Other features and advantages of the invention will become apparent from the following detailed description of the preferred embodiments, taken in conjunction with the accompanying drawings, which illustrate, by way of example, the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

15 FIG. 1 is a schematic representation of a cooling system embodying features of the present invention.

FIG. 2 is a cross-sectional view of a sprayer for the cooling system represented in FIG. 1.

20 FIG. 3 is a cut-away perspective view of a first embodiment of the cooling system represented in FIG. 1.

FIG. 4 is a cross-sectional view of the embodiment depicted in FIG. 3.

FIG. 5 is a cut-away perspective view of a second embodiment of the cooling system represented in FIG. 1.

FIG. 6 is a cross-sectional view of a third embodiment of the cooling system represented in FIG. 1.

5 FIG. 7 is a control system block diagram for controlling the operation of the embodiment depicted in FIG. 6.

FIG. 8 is a control system block diagram for controlling the operation of the embodiment depicted in FIG. 5.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

10 An embodiment of a cooling assembly 10 for cooling a heat-generating semiconductor device 12, according to the present invention, is schematically shown in FIG. 1. The assembly includes a one or more incremental sprayers 14 for spraying an incremental amount of a liquid cooling fluid 16, preferably from a reservoir 18, onto the semiconductor device to evaporatively cool the semiconductor device. The
15 assembly also includes a heat exchanger 20 to extract the heat from the vaporized cooling fluid, and thereby liquify or condense it. The assembly further includes a pump 22 to pump the liquified cooling fluid back into the reservoir that feeds the sprayers.

20 While incremental sprayers 14 that can be used as part of the present invention can be based on other types of ink-jet droplet expelling technology, such as piezoelectric technology (i.e., piezoelectric nozzles), they are preferably based on thermal ink-jet technology. Examples of this technology are discussed in numerous

U.S. Patents, including Nos. 5,924,198, 4,500,895, and 4,683,481, which are incorporated herein by reference. Other thermal ink-jet technologies can likewise be appropriate for use with this invention. A highly preferable cooling fluid for use with a thermal incremental sprayer is 3M Fluorinert[®], which is easily adaptable to existing thermal ink-jet technology because it has a viscosity and boiling point similar to that of the inks typically used in ink-jet printers.

With reference to FIG. 2, which depicts two simplified, exemplary incremental sprayers 14, each sprayer includes structure defining a chamber 30 for receiving a predetermined portion of the cooling fluid and a heater 32 for vaporizing a portion of the cooling fluid, to create the pressure to eject an incremental amount of the cooling fluid through an orifice 34 that directs the ejected cooling fluid toward the semiconductor device 12 (FIG. 1). The orifices are formed in a flexible polymer tape 36, e.g., tape commercially available as Kapton TM tape, from 3M Corporation.

Affixed to a back surface 38 of the tape 36 is a silicon substrate 40 containing the heaters 32, in the form of individually energizable thin-film resistors. Each heater is preferably located on a side of the chamber 30 across from the chamber's orifice 34. Cooling fluid is preferably drawn and loaded into the chamber by capillary action, as is typical for an ink-jet type device. A computerized controller (not shown) energizes the heater, vaporizing the portion of the cooling fluid adjacent to the heater. The vaporized cooling fluid expands, expelling most of the non-vaporized cooling fluid out of the orifice, typically in the form of a single droplet.

Depending on the configuration of the sprayer, the incremental amount of the fluid sprayed from the sprayer could be in the form of a single droplet, or in the form of multiple droplets. Multiple droplets could be produced by multiple orifices related to a single heater, or by sprayers having larger chamber volumes and appropriately shaped orifice nozzles to cause the incremental amount of fluid to break

into droplets. After the chamber has been fired by the heater, capillary action again loads the chamber for a subsequent firing.

5 The liquid spray from the incremental sprayers 14 can be highly controllable. For example, by increasing or decreasing the frequency that the sprayers are energized, the flow rate can be accurately adjusted. Furthermore, because the sprayers can be configured to deliver very small quantities of cooling fluid, and because a large number of sprayers can be fit into a small area, the heat distribution over that area can be accurately controlled by energizing some of the sprayers at a rate greater than that of other sprayers.

10 With reference again to FIG. 1, to aid the reservoir 18 in providing the cooling fluid to the incremental sprayers 14, the reservoir can be configured with a spring assist mechanism 42. Alternatively, the reservoir can be positioned such that the cooling fluid receives a gravity assist in flowing to the sprayers 14. In addition to serving as a source of liquid cooling fluid, the reservoir also serves to separate any gas
15 leaving the condenser. A filter (not shown) can be used, either in the reservoir or in some other portion of the system, to remove board level contaminants that are present in the system.

20 The pump 22 serves to replenish the reservoir 18, and can be a low-cost apparatus that does not provide either high pressure or consistent and controlled flow. Preferably the pump should be self priming to remove trapped gas.

25 The precise order of the components can be varied. For example, the pump 22 could be placed prior to the heat exchanger 20, so long as it can pump both vapors and fluids. Likewise, depending on the type of sprayer, the reservoir could be eliminated, and the pump could be used to directly feed the sprayers 14. The entire assembly 10, including the circuit board, is preferably a field-replaceable unit.

With reference now to FIGS. 3 and 4, multiple cooling systems within one computer (or other device) can be configured to share components. The computer can contain a plurality of circuit boards 50 carrying heat-generating components 52 such as CPUs, each circuit board typically being mounted on a backplane 54.

5 Incremental sprayers 56 are located adjacent to the components, and are configured to spray the components with a cooling fluid. The components and sprayers are enclosed in a compartment 58 that prevents vaporized cooling fluid from escaping the system. A roll bond panel 60 serves as a first heat exchanger, condensing some or all of the vapor. The roll bond panel is formed as a wall of the sealed compartment. Suitable

10 roll bond panels can be obtained from Showa Aluminum Corporation, of Tokyo, Japan, or from Algoods, of Toronto, Canada. A suitable low-boiling point working fluid, e.g., 3M Fluorinert®, is carried within fluid channels in the roll bond panel. Alternatively, working fluids such as hydrofluoroether or alcohol could be used.

A second heat exchanger 62, which can also be a roll bond panel, is

15 located externally from the circuit board compartments 58, and provides for the additional condensing of vaporized cooling fluid. The second heat exchanger receives the cooling fluid, which can be both liquid and vaporized, from the compartments of each circuit board 50. After the cooling fluid has been further cooled by the second heat exchanger, a commonly shared pump 64 delivers the cooling fluid to a commonly

20 shared reservoir 66, which in turn returns the cooling fluid to the sprayers 56 of each circuit board.

With reference now to FIG. 5, the entire cooling system can be incorporated into a single circuit board assembly 70. The circuit board assembly will typically include heat-generating components 72 such as CPUs, mounted on a circuit

25 board 74. Incremental sprayers 76 are located adjacent to the components, and are configured to spray the components with a cooling fluid. The components and sprayers are enclosed in a sealed compartment 78 that prevents vaporized cooling fluid from

escaping. One or more roll bond panels 80 preferably are incorporated into one or more compartment walls, and are configured to condense vapor and release it into a collection reservoir 82 in the bottom of the circuit board assembly. The pool also receives non-vaporized coolant that drips from the components. A pump 84 pumps the cooling fluid up into a main feed reservoir 86, preferably being above the sprayers, which provides the cooling fluid to the sprayers. As an alternative to the reservoir's being located above the sprayers, which causes a gravity feed effect, the reservoir could incorporate some type of pressure mechanism, such as a spring.

Generally speaking, for embodiments of the invention to function at optimal efficiency, the sprayers' mass flow rate ($\dot{m}_s$) should be adjusted to avoid having the semiconductor device become either dry or immersed. This rate is controlled by having a controller adjust the rate that the thermal jets are fired. The optimum mass flow rate can change as the heat flux of the semiconductor device changes. Thus, for a controller to correctly control the mass flow, parameters of the semiconductor device and/or cooling system need to be sensed.

To determine whether the mass flow rate is at an optimal level, sensors can be used to track one or more of the system parameters. The types of parameters that are available vary with the type of system employed. For example, if the heat exchanger is external to the chamber where the spraying occurs, then the liquid and the vapor can be removed from the chamber through separate passages (with the assistance of a resistive mesh to inhibit entry of vapor into the liquid passage), and the mass flow of the vapor ($\dot{m}_v$) and/or mass flow of the liquid ($\dot{m}_l$) are available to be measured. However, these are not available if the heat exchanger is within the spray chamber, such as in the embodiment of FIG. 5. Instead, the vapor pressure within the spray chamber (P_v) and the semiconductor device's junction temperature can be sensed.

FIG. 6 depicts a cooling system 90 having a heat exchanger 92 external to a spray chamber 94. The spray chamber contains incremental sprayers 96 that spray a cooling fluid onto semiconductor devices 98 on a circuit board 100. Depending on the temperature of the semiconductor devices, some of the cooling fluid may vaporize, and some may run off to form a pool 102. Vapor exits the spray chamber through a vapor passage 104, while liquid exits via a liquid passage 106. A mesh 108 is used to prevent vapor from entering the liquid passage, while gravity prevents the liquid from entering the vapor passage. The vapor and liquid are combined and inserted into the heat exchanger 92, which removes heat and liquefies the vapor. A pump 110 draws the cooled cooling fluid up into a reservoir 112, where it is again provided to the sprayers.

A number of potentially useful system parameters can be sensed in this system, including: The temperature of the semiconductor devices (T_j) (i.e., the junction temperature), which can often be sensed from within the device; The ambient temperature (T_a) and pressure (P_a), as well as the vapor pressure (P_v), in the spray chamber 94, which can be sensed using temperature and pressure sensors 114 within the spray compartment; The mass flow of the vapor ($\dot{m}_v$) and the mass flow of the liquid ($\dot{m}_l$), which can be sensed using appropriate sensors 116, 118 in respective vapor and liquid passages 120, 122; The temperature (T_{sc}) of the sub-cooled liquid coming out of the heat pump 92, which can be sensed by a temperature sensor; And the temperature (T_l) of the liquid being received by the sprayer.

With reference to FIG. 7, a method of adjusting the sprayers' mass flow rate ($\dot{m}_s$) for the device depicted in FIG. 6 begins with the steps of by starting the cooling system 120 and setting 122 the sprayers' initial mass flow rate at an initial value ($\dot{m}_{s,init}$). This value typically would be based on prior experience with this system, or with systems of its type, but could also be based on calculated heat generations rates and cooling rates. A limited amount of time (t) is preferably allowed to pass 124 so that the system can begin functioning, and then the sensing logic begins

to take action, i.e., the cooling system begins sensing and monitoring parameters and adjusting the sensors' mass flow rate.

In particular, the temperature of the semiconductor devices (T_j) is sensed 126, and the resulting sensor value is compared 128 to a selected maximum value T_{max} .
5 If the resulting sensor value is below the selected maximum value then no action is taken, and the monitoring of parameters is repeated. If, however, the semiconductor device has reached the selected maximum value, then sensors are used to determine if pooling is occurring. Preferably, to detect pooling, the mass flow of the vapor ($\dot{m}_v$) is sensed 130 and compared 132 to a selected minimum value ($\dot{m}_{v,min}$) to verify that it is
10 above that value $\dot{m}_{v,min}$. The selected minimum value ($\dot{m}_{v,min}$) typically would be based on prior experience with this system, or with systems of its type, but could also be based on calculated heat generations rates and cooling rates.

If the mass flow of the vapor ($\dot{m}_v$) is above the selected minimum value, then pooling is not a problem, and the sprayers' mass flow rate should be increased 134
15 to reduce the temperature (T_j). However, if the mass flow rate of the vapor is not above the minimum value, then pooling is occurring and the sprayers' mass flow rate is decreased 136 to increase the cooling system's effectiveness. After the sprayers' mass flow rate is incrementally adjusted, either up or down, the monitoring is continued by again sensing the temperature of the semiconductor devices (T_j). It
20 should be noted that the orientation of the sprayed surface (with respect to gravity) might have an effect on the accurate sensing of pooling, and that experimentation can be used to verify and/or adjust the selected minimum value $\dot{m}_{v,min}$ accordingly.

In the alternative, other sensors can be used to determine if pooling is occurring. For example, the vapor pressure (P_v) in the spray chamber is a more direct
25 measure of whether pooling is occurring.

FIG. 8 is a flowchart depicting a method of adjusting the sprayers' mass flow rate ($\dot{m}_s$) for a cooling device having an internal heat exchanger, such as the device depicted in FIG. 5. The method begins with the steps of starting the cooling system 140 and setting the sprayers' initial mass flow rate 142 at an initial value ($\dot{m}_{s,init}$).

5 This value typically would be based on experimentation, and/or prior experience with this system or systems of its type, but it could be based on an analysis of temperature generation rates and cooling rates. A limited amount of time (t) is preferably allowed to pass 144 prior to starting the actions of the sensing logic, so that the system can begin functioning, and the cooling system can begin sensing and monitoring parameters and adjusting the sensors' mass flow rate. The time (t) is related to the time constant
10 of the system, i.e., the time needed for the system to reach operating temperatures.

In particular, the temperature of the semiconductor devices (T_j) is sensed 146, and the resulting sensor value is compared 148 to a selected maximum value T_{max} . If the resulting sensor value is below the selected maximum value then no action is
15 taken, and the monitoring of parameters is repeated. If, however, the semiconductor device has reached the selected maximum value, then sensors are used to determine if pooling is occurring. Preferably, to detect pooling, the vapor pressure (P_v) in the spray chamber is sensed 150 and compared 152 to a selected minimum value ($P_{v,min}$) to verify that it is above the selected minimum value. To aid in the accurate sensing of the vapor
20 pressure, the system is preferably configured with an internal pressure below atmospheric pressure. The selected minimum value ($P_{v,min}$) is not easy to calculate, and is preferably determined empirically.

If the vapor pressure (P_v) in the spray chamber is above the selected minimum value, then pooling is not a problem, and the sprayers' mass flow rate should
25 be increased 154 to reduce the temperature (T_j). However, if the vapor pressure (P_v) is not above the minimum value, then pooling is occurring and the sprayers' mass flow rate is decreased 156 to increase the cooling system's effectiveness. After the sprayers'

mass flow rate is incrementally adjusted, either up or down, the monitoring is continued by again sensing the temperature of the semiconductor devices (T_j).

More generally, it will be seen that any sensor reading indicative of the semiconductor's temperature, including direct readings or indirect readings (such as heat dissipation when the heat generation rate is known) can be used to judge whether the cooling is adequate. Furthermore, it will be seen that any sensor reading indicative of pooling, such as vapor flow rate, liquid flow rate, vapor pressure, or others, can be used to judge whether the cooling would be improved by increasing or decreasing the spray flow rate. Additionally, it will be appreciated that, while the order of sensing and decision making contributes to the efficiency of the system, it can be varied within the scope of the invention. For example, both temperature and pooling can be sensed prior to any comparisons. Likewise, pooling can be sensed and compared to a reference value prior to sensing the semiconductor (or other heat-generating device) temperature.

From the foregoing description, it will be appreciated that the present invention provides an accurate, reliable and cost efficient spray cooling system. The system includes a sprayer configured to deliver cooling fluid to a heat-generating device in limited increments. Preferably, the sprayer is thermally driven in a fashion similar to that of an ink-jet print head.

While a particular form of the invention has been illustrated and described, it will be apparent that various modifications can be made without departing from the spirit and scope of the invention. Thus, although the invention has been described in detail with reference only to the preferred embodiments, those having ordinary skill in the art will appreciate that various modifications can be made without departing from the invention. Accordingly, the invention is not intended to be limited, and is defined with reference to the following claims.

We Claim:

1. A cooling assembly for cooling a heat source with a cooling fluid, comprising:
an incremental sprayer configured to eject an incremental amount of the
cooling fluid on the heat source in response to a control signal; and

5 a controller configured to send the control signal to the incremental
sprayer.

2. The cooling assembly of claim 1, wherein the incremental sprayer comprises:
a body defining a chamber configured to hold a volume of the cooling
fluid, and defining an orifice in communication with the chamber; and

5 a heating element in thermal communication with the chamber, the
heating element being configured to vaporize a portion of the cooling fluid held within
the chamber;

wherein the orifice is configured to direct cooling fluid from the chamber
to the heat source upon the heating element vaporizing a portion of the cooling fluid
held within the chamber.

3. The cooling assembly of claim 2, wherein:

the body includes a thin-film substrate and a backing;

the chambers are cavities that are formed adjoining one side of the thin-
film substrate by the backing;

5 the orifice is a passage through the thin-film substrate; and

the heating element is a thin-film resistor.

4. The cooling assembly of claim 1, wherein the incremental amount of the cooling
fluid is a single droplet of cooling fluid.

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5. The cooling assembly of claim 1, wherein the incremental sprayer comprises a piezoelectric nozzle.
6. The cooling assembly of claim 1, and further comprising a heat exchanger configured to cool and condense cooling fluid that was vaporized by the heat source after being ejected by the incremental sprayer.
7. The cooling assembly of claim 6, wherein the heat exchanger is a roll bond panel.
8. The cooling assembly of claim 1, and further comprising a reservoir configured to provide liquid cooling fluid to the incremental sprayer.
9. The cooling assembly of claim 1, and further comprising:
a heat exchanger configured to cool and condense cooling fluid that was vaporized by the heat source after being ejected by the incremental sprayer;
a reservoir configured to provide liquid cooling fluid to the incremental
5 sprayer; and
a pump configured to pump liquid cooling fluid from the heat exchanger to the reservoir.
10. A cooled circuit board, comprising:
a circuit board;
a semiconductor device mounted on the circuit board; and
the cooling assembly of claim 1 configured to cool the semiconductor
5 device.



11. The cooled circuit board of claim 10, and further comprising:

a heat exchanger configured to cool and condense cooling fluid that was vaporized by the semiconductor device after being ejected by the incremental sprayer;

5 a reservoir configured to provide liquid cooling fluid to the incremental sprayer; and

a pump configured to pump liquid cooling fluid from the heat exchanger to the reservoir.

12. A cooled circuit board assembly, comprising:

a plurality of the cooled circuit boards of claim 10;

5 a heat exchanger configured to cool and condense cooling fluid that was vaporized by the semiconductor device of each of the plurality of cooled circuit boards after being ejected by the incremental sprayer;

a reservoir configured to provide liquid cooling fluid to the incremental sprayer of each of the plurality of cooled circuit boards; and

a pump configured to pump liquid cooling fluid from the heat exchanger to the reservoir.

13. The cooled circuit board assembly of claim 12, wherein each of the plurality of cooled circuit boards includes a roll bond panel configured to cool and condense cooling fluid that was vaporized by the semiconductor device after being ejected by the incremental sprayer.

14. A method of cooling a heat source, comprising:

ejecting an incremental amount of a cooling fluid onto the heat source using an incremental sprayer; and

repeating the step of ejecting at time increments.



15. The method of claim 14, wherein the step of spraying comprises:

providing cooling fluid to a chamber defined in the incremental sprayer;
energizing a heating element in thermal communication with the chamber
to vaporize a portion of the cooling fluid within the chamber;

5 wherein the incremental sprayer defines an orifice in communication with the chamber, the orifice being configured to direct cooling fluid from the chamber to the heat source upon the heating element's vaporizing of a portion of the cooling fluid in the chamber.

16. The method of claim 15, wherein:

in the step of providing, the chamber is a cavity formed in a backing, the cavity adjoining a thin-film substrate;

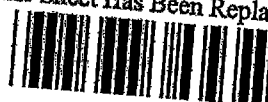
the orifice is a passage through the thin-film substrate; and
5 in the step of heating, the heating element is a thin-film resistor.

17. The method of claim 14, and further comprising:

sensing the temperature of the heat source;
sensing the pooling of the sprayed cooling fluid;
adjusting the mean flow rate of cooling fluid ejected by the incremental
5 sprayer based on the sensed temperature of the heat source and pooling of the sprayed cooling fluid.

18. The method of claim 17, wherein the mean flow rate is adjusted by adjusting the frequency with which the step of ejecting is repeated.

19. The method of claim 14, wherein the step of repeating is conducted with a frequency that varies with a sensed indication of pooling of the sprayed cooling fluid.



20. The method of claim 14, and further comprising:

sensing the temperature of the heat source;

sensing whether pooling is occurring; and

varying the frequency with which the step of repeating is conducted

5 based upon the sensed temperature and the sensed result of whether pooling is occurring;

wherein if the sensed temperature is above a previously determined maximum temperature and the sensed result of whether pooling is occurring indicates that pooling is occurring, the frequency with which the step of repeating is conducted

10 is varied downward in the step of varying; and

wherein if the sensed temperature is above a previously determined maximum temperature and the sensed result of whether pooling is occurring indicates that pooling is not occurring, the frequency with which the step of repeating is conducted is varied upward in the step of varying.

21. A method of cooling a heat source, comprising:

spraying a cooling fluid onto the heat source;

sensing whether pooling of the sprayed cooling fluid is occurring; and

5 varying the flow rate of the spraying based upon the sensed indication of whether pooling is occurring.

22. The method of claim 21, and further comprising sensing the temperature of the heat source, wherein, in the step of varying, the flow rate is also varied based upon the sensed temperature.

