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(54) **HEAT PIPE WITH NANOSTRUCTURED WICK**

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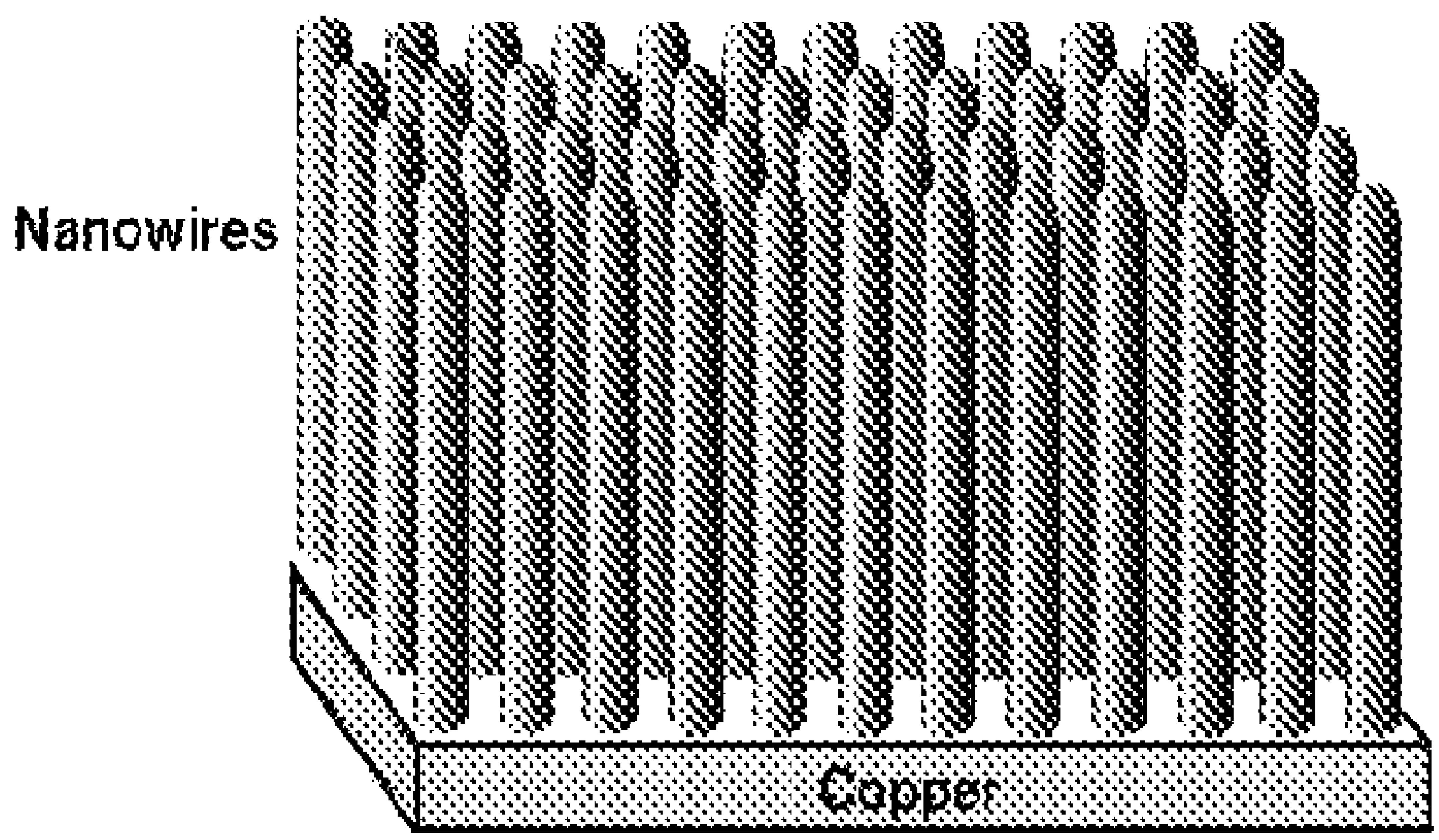
(57) **ABSTRACT**

A heat pipe with a nanostructured wick is disclosed, with the method of forming the nanostructured wick on a metal substrate. The wicking material is a pattern of metallic nanostructures in the form of bristles or nanowires attached to a substrate, where the bristles are substantially freestanding.



SchematicDiagram of a nanobristle array.

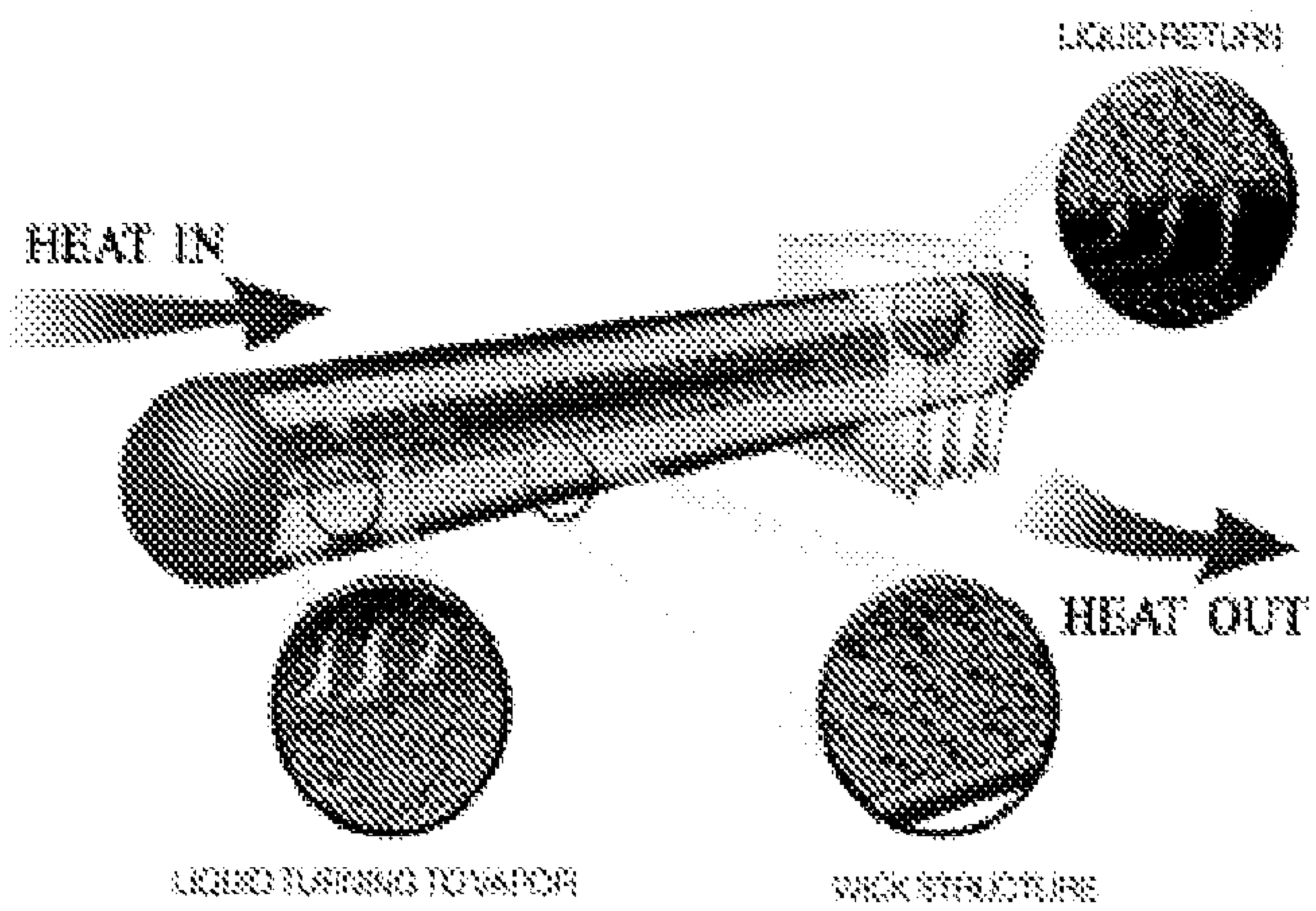


Figure 1 Schematic representation of the heat pipe thermal cycle heat transfer mechanism.

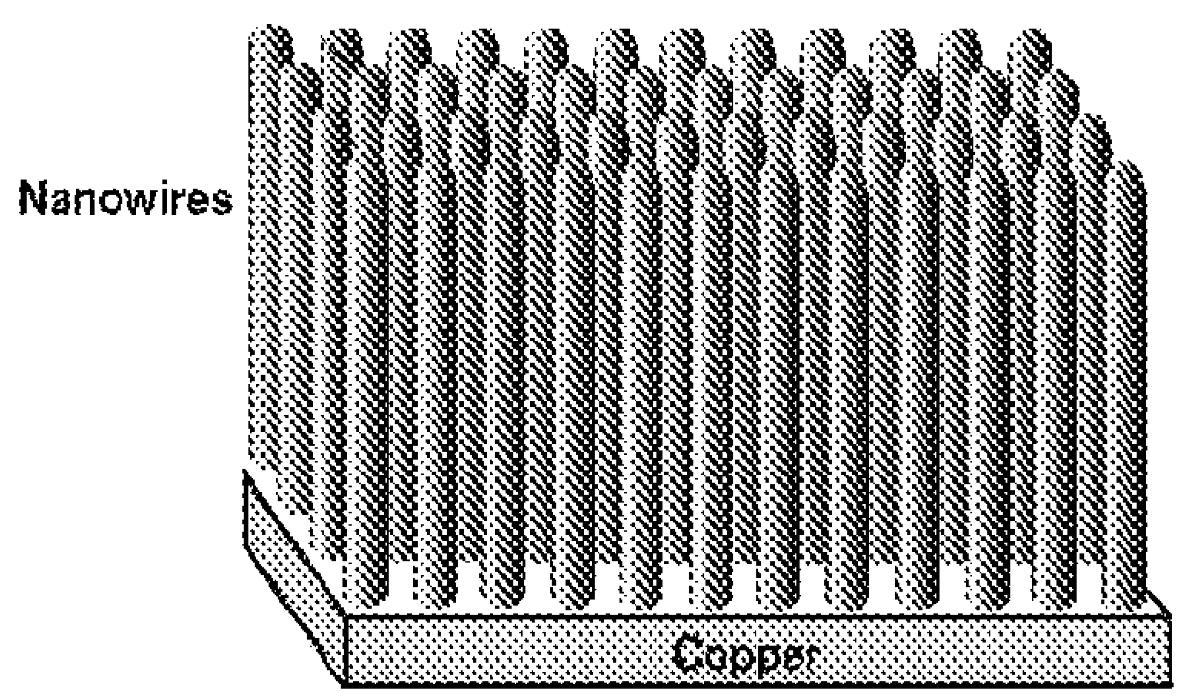


Figure 2 SchematicDiagram of a nanobristle array.

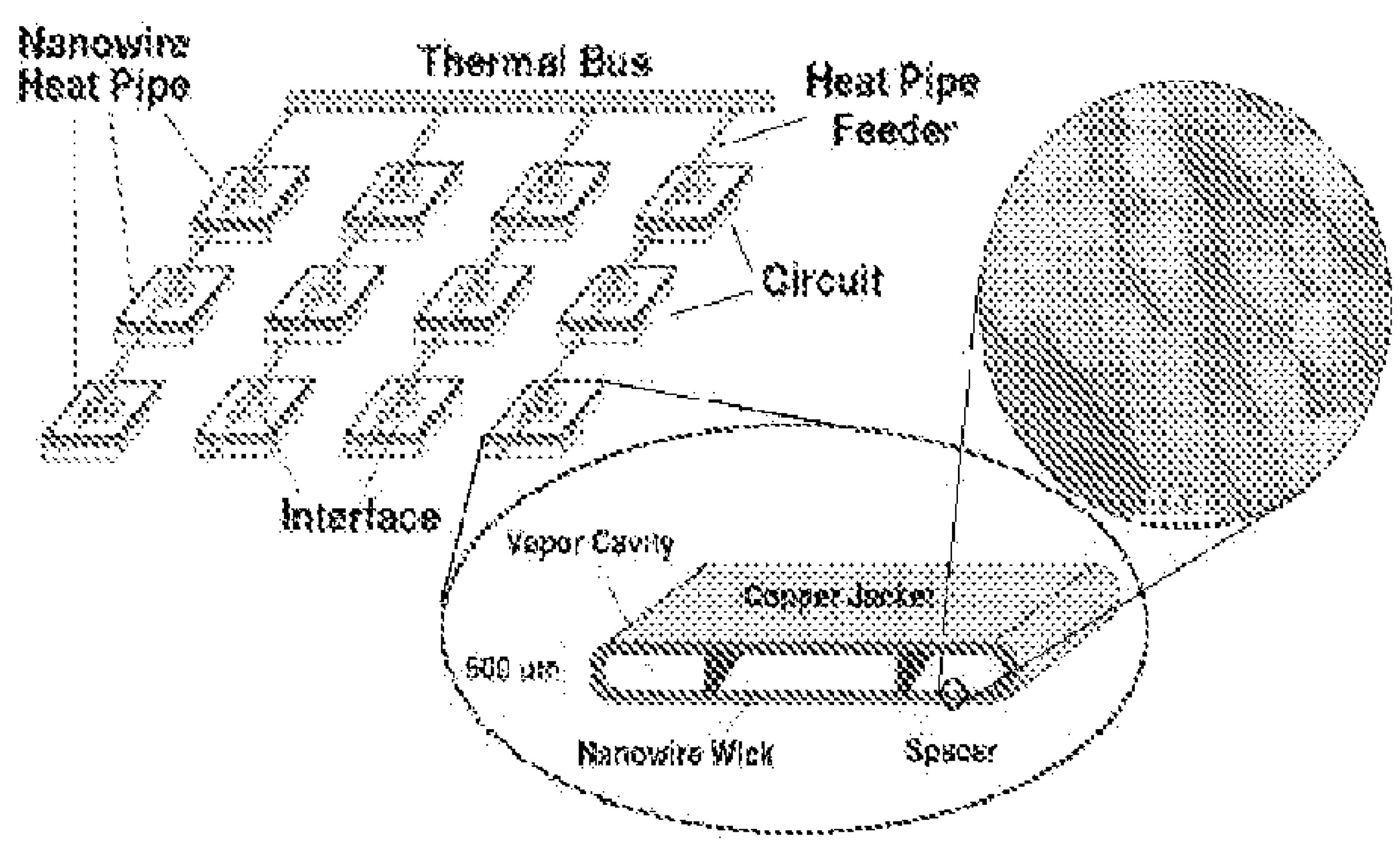


Figure 3 Electronic systems thermal management concept utilizing nanobristle wick heat pipes. The inset is an SEM image of copper nanobristles.

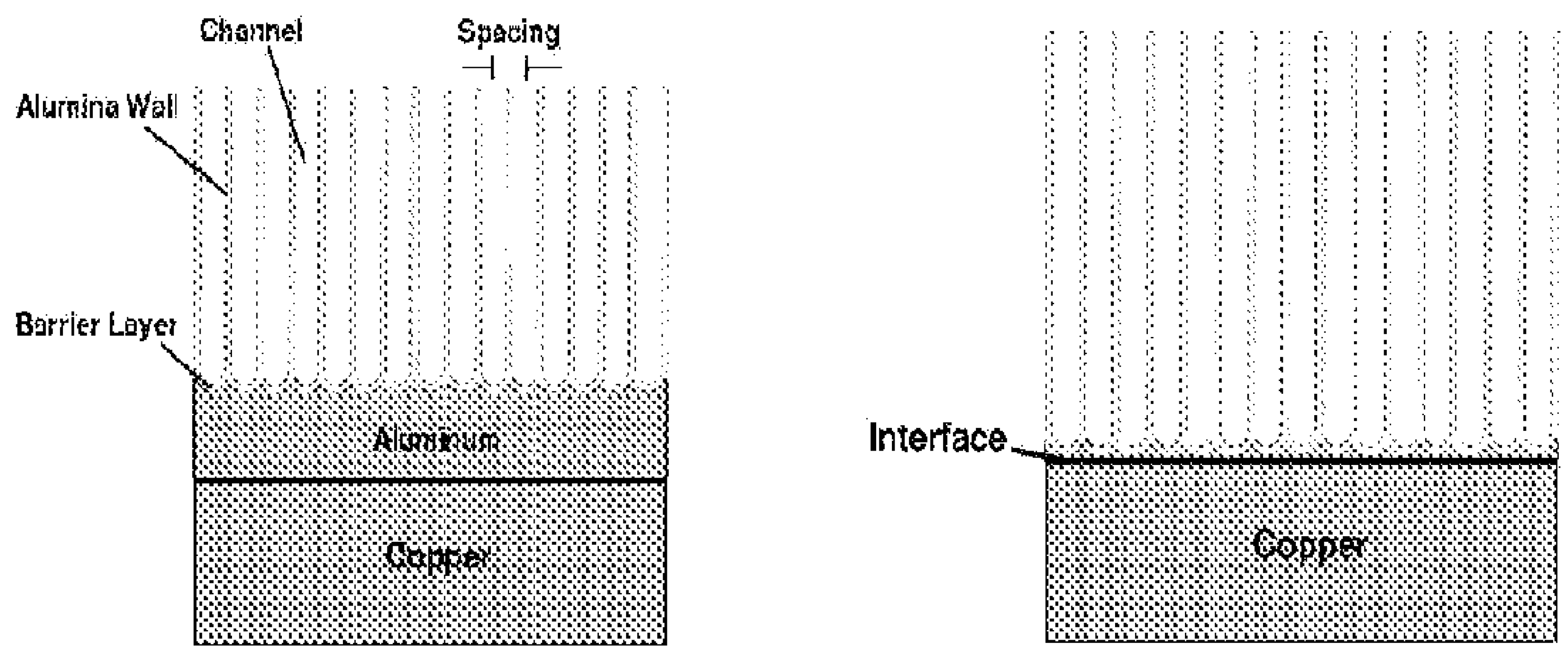


Figure 4 Schematic of porous anodized aluminum oxide on a copper substrate. The spacing between channels, the channel diameter and the channel depth are all controllable parameters.

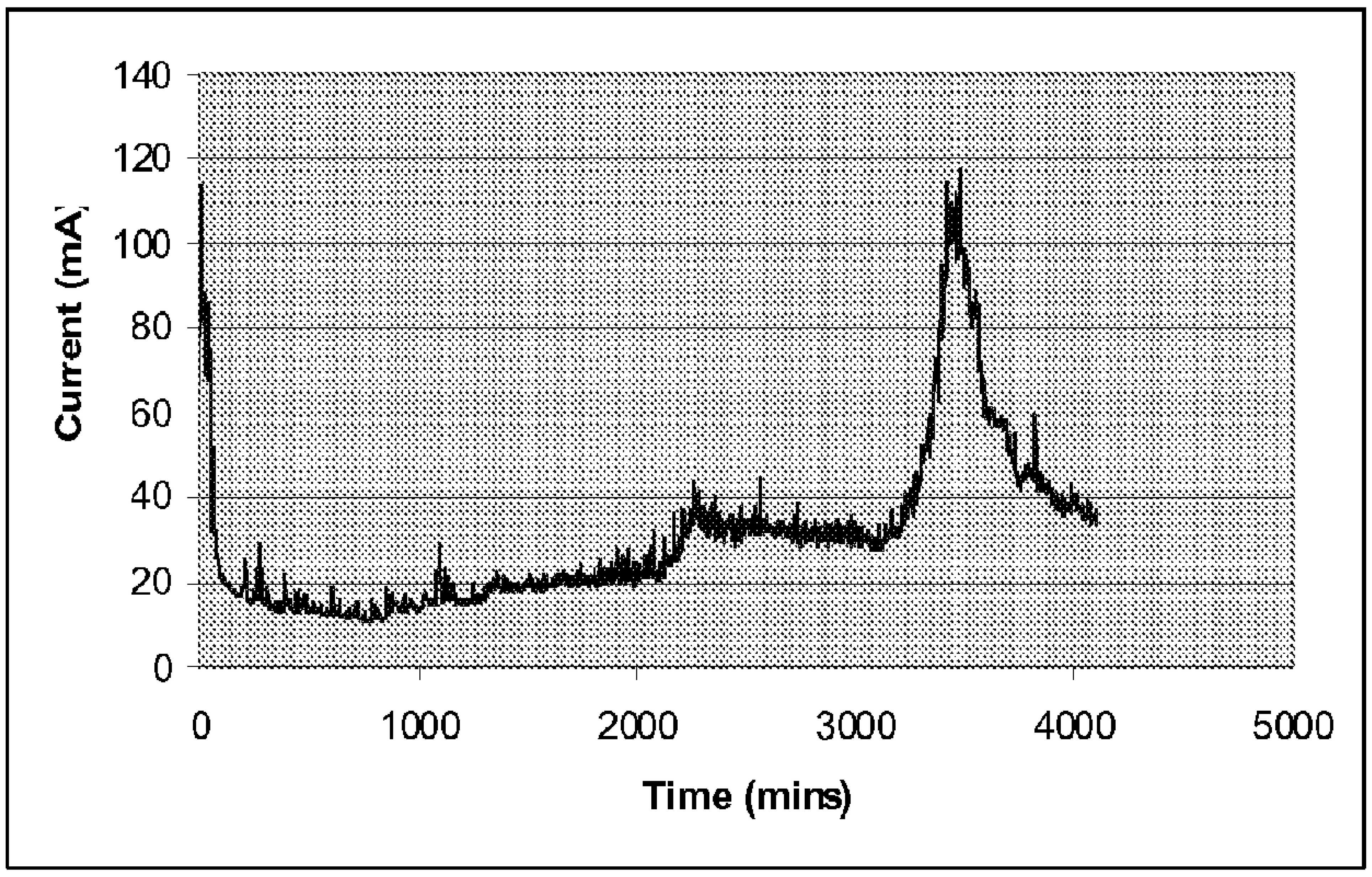


Figure 5 Plot of current vs. time for the formation of the alumina nanochannels. The increase in current corresponds to the nanochannels reaching the copper substrate.

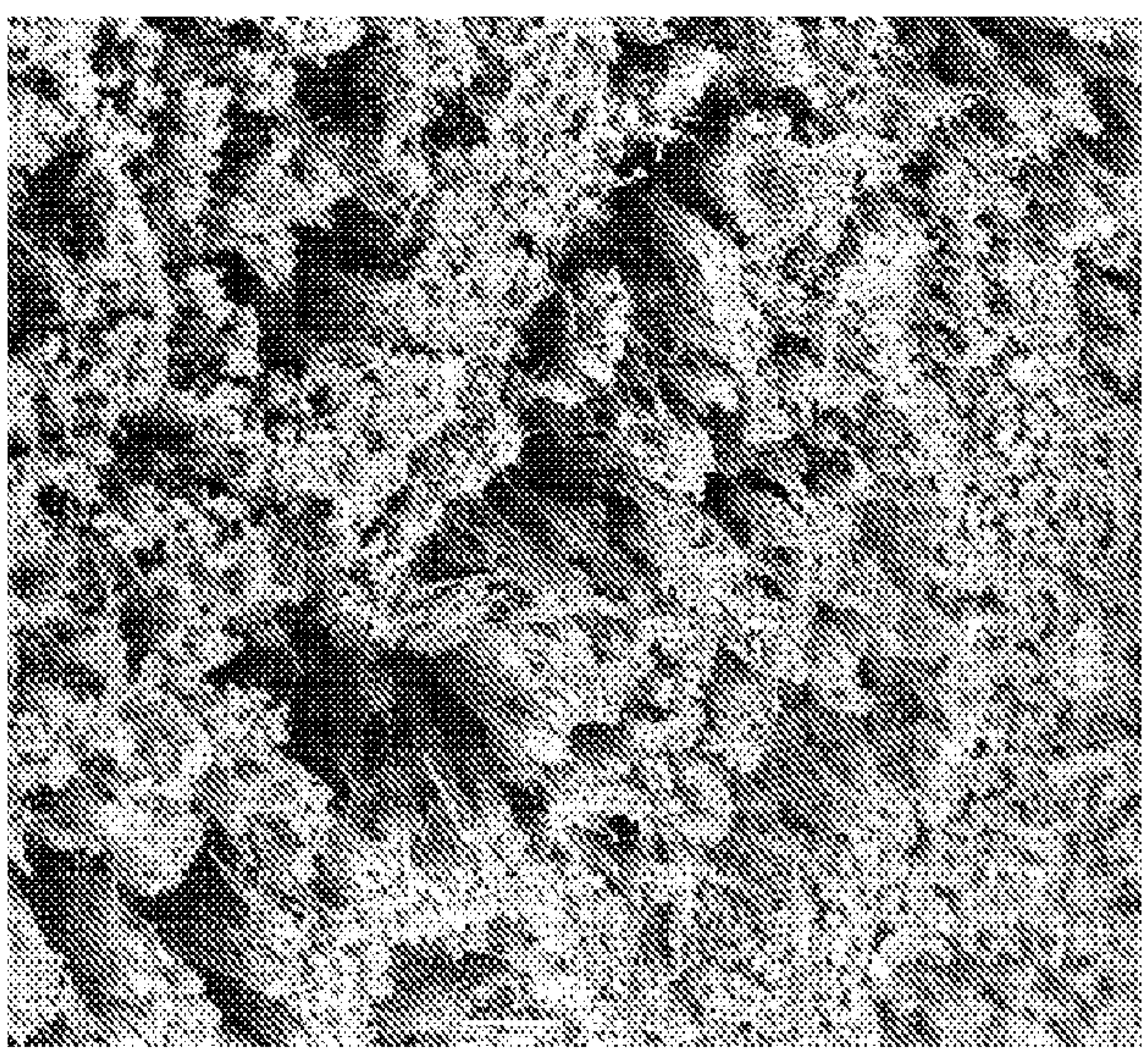


Figure 6. SEM image of copper nanobristles formed from aluminum clad onto a copper substrate.

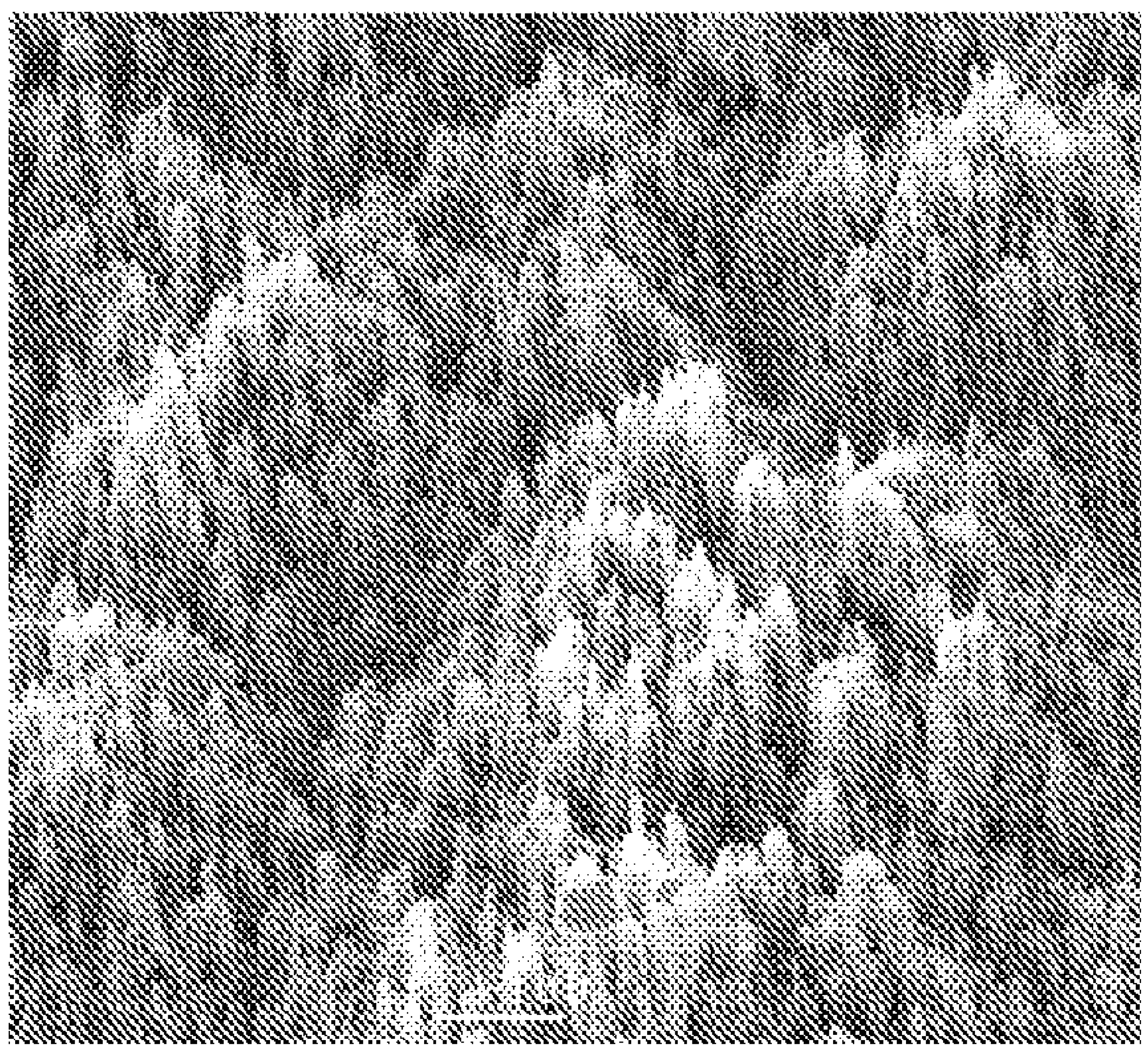


Figure 7 SEM Image of copper nanobristles formed using an Anodisc filter template held onto a copper substrate.

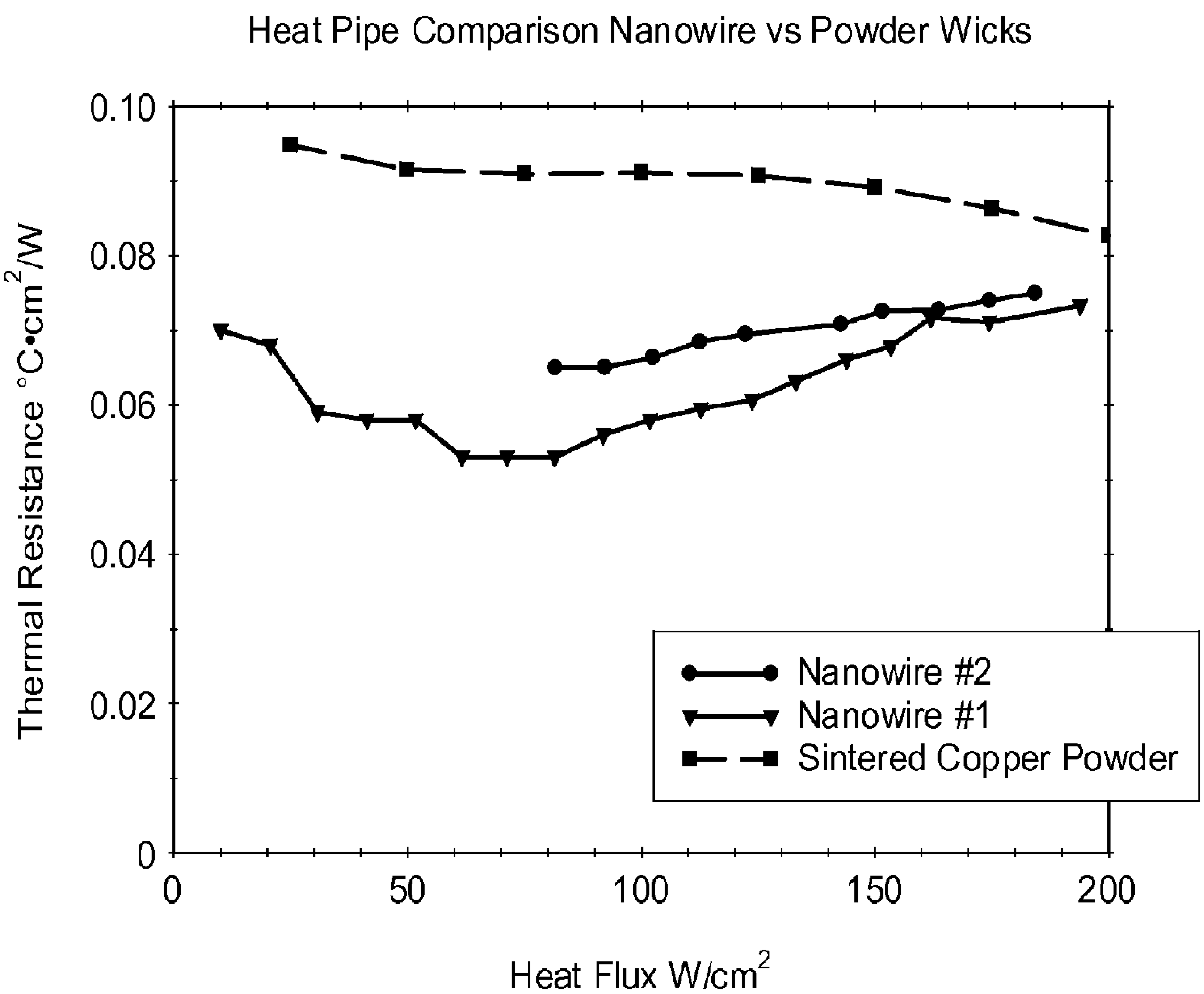


Figure 8. Thermal Resistance vs. Input Heat Flux for heat pipes with nanobristle array wicks. Solid line is published data for sintered powder heat pipes tested under the same conditions.

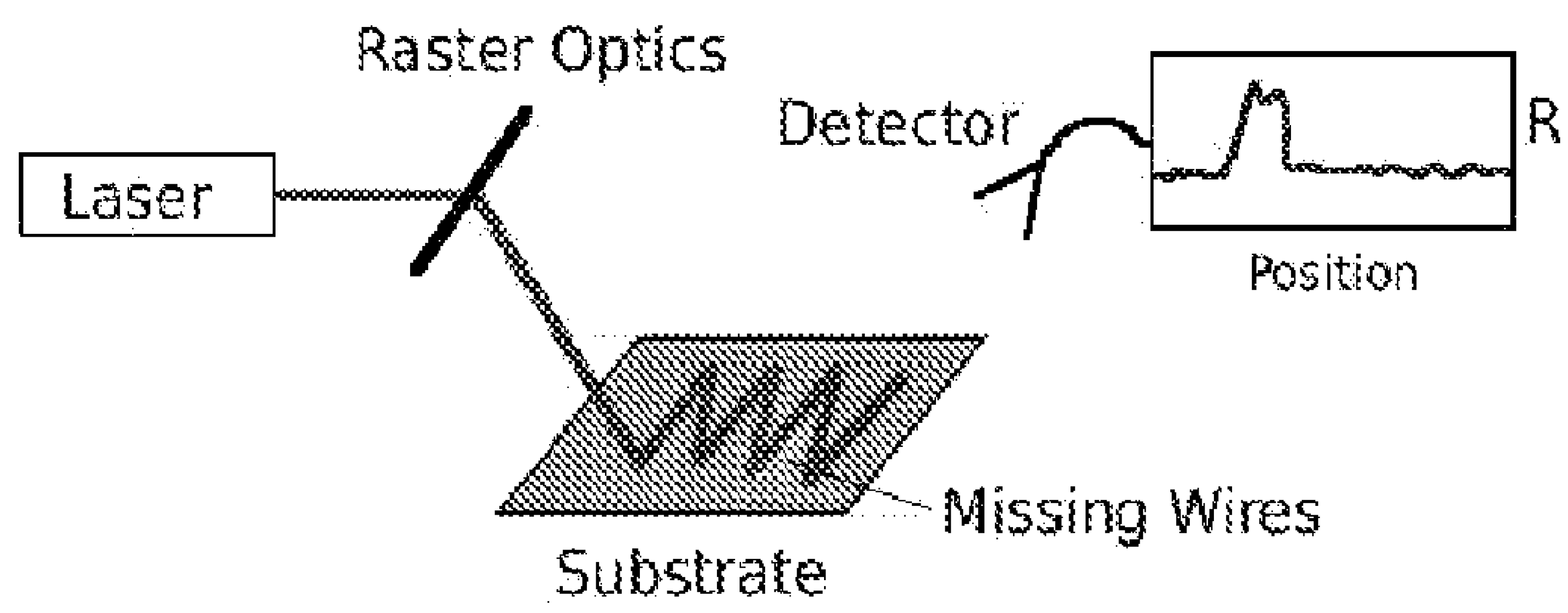


Figure 9 Reflectivity inspection for missing nanobristles in the nanobristle array. A rastering laser and photodiode can be used to find patches of missing bristles on a continuously moving nanobristle wick tape.

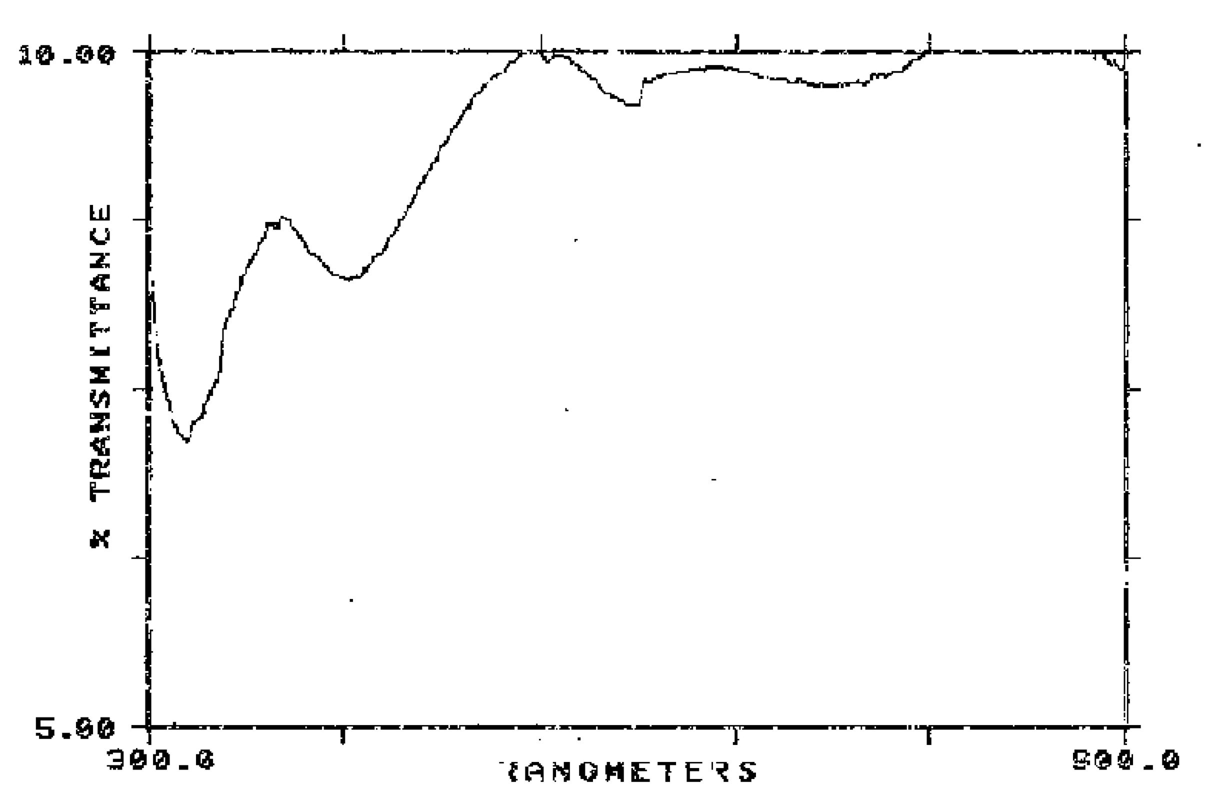


Figure 10 UV-Visible spectrum of copper nanobristle array. The two absorption bands are due to the localized surface plasmon resonance.

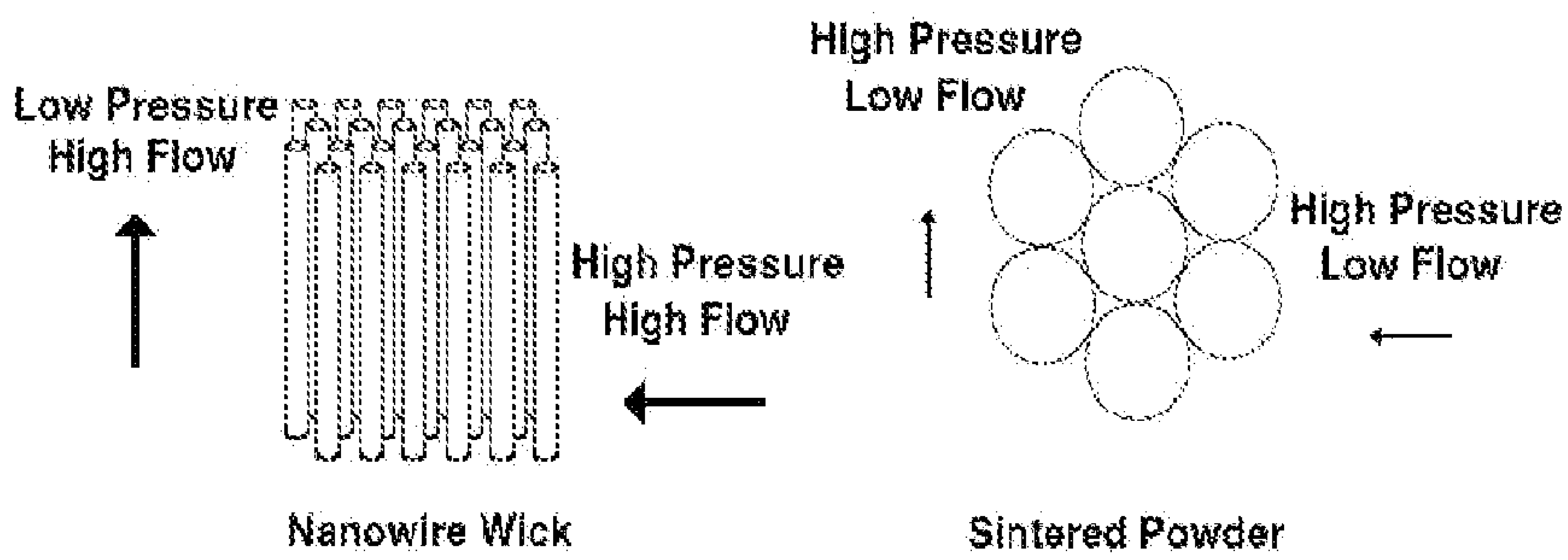


Figure 11 Illustrated comparison of fluid flow in nanowire and sintered powder heat pipc wicks.

HEAT PIPE WITH NANOSTRUCTURED WICK

[0001] This application claims priority to U.S. Pat. App. No. 66/778,873, filed on Mar. 3, 2006, which is hereby incorporated herein by reference for all that it teaches and to U.S. Pat. App. No. 60/888,391, filed on Feb. 6, 2007, which is hereby incorporated herein by reference for all that it teaches.

[0002] This invention was supported in part by U.S. Government contract number Phase I SBIR Navy Contract N65540-03-0055 and NSF Phase 165618840 and portions of this invention may be subject to a paid-up license to the U.S. Government.

BACKGROUND AND SUMMARY OF THE INVENTION

[0003] Heat pipes are the method of choice for electronic systems thermal management because of the performance advantages they have over conventional aluminum extrusion heat sinks and other solid state cooling technologies. A heat pipe cooler uses the high efficiency evaporation and condensation cycles of a working fluid to transfer heat as shown in FIG. **1**. Compared to other cooling techniques, such as forced single and two-phase flow cooling, thermoelectrics, fans, and direct immersion cooling, heat pipes do not require mechanical pumps, switches, valves or consume any power. Consequently heat pipes are quieter, more efficient, have no operating cost and are more reliable than other thermal management systems. The functional components of a heat pipe are the wick, the working fluid, and the package housing them.

[0004] Heat pipes are passive, closed loop devices used for temperature regulation in electronic and optical systems. Heat pipes are used for transporting heat from electronic device components and packages to a heat sink. For example, in a lap top computer a heat pipe is used to transfer heat from the CPU to the case of the computer to keep the CPU from overheating. In general, the heat transfer can take place between any source (hot) to a sink (cold). With the increasing power demands of integrated electronic, optical, and mechanical systems, localized thermal management is a critical issue for proper device operation. The typical heat pipe is an enclosed tube-like structure or other enclosed package that is typically made of metal where the interior surface of the enclosure has a wicking structure. The wick acts on a coolant (working fluid) in a liquid phase to move the working fluid from the sink (condenser) to the source (evaporator) by means of capillary action. The center of the heat pipe enclosure is open and free of obstruction. The working fluid moves through the wick to the evaporator, in the opposite direction of the gas phase that moves in the open space to the condensor. At the hot end of the device, a phase change from liquid into vapor occurs, while at the cool side, the phase change from vapor into liquid occurs. Heat transport is accomplished by the removal of heat through the latent heat of evaporation and cooling through the latent heat of condensation. The wicking material passively transports the liquid thus making a cycle that continuously cools the heat generating element. The center of the heat pipe continuously transports the vapor via a pressure differential between the hot and cold ends of the heat pipe

[0005] The invention is a heat pipe where the wicking structure is nanostructured, meaning that the cross sectional dimension of the elementary structures comprising the wicking material are on the order of approximately 10 to 400 nanometers with spacings between the elements between approximately 20 to 600 nanometers, center to center that residing within the interior surface of the enclosed space (package) of the heat pipe and a method of making the nanostructures. In the preferred embodiment, the nanostructures are bristles or a plurality of nanowires that are attached on one end to the interior surface of the heatpipe. By nanowire, it is meant a wire whose cross sectional dimension is between approximately 10 nanometers and approximately 400 nanometers. The nanowires are also substantially free-standing, that is, they are surrounded on the sides by the working fluid in either the liquid phase or gas phase, not a substrate other than the substrate they are grown on, template or other support material. Groups of nanowires are also referred to herein as bristles or nanobristles. The nanostructured wicking material provides improved capillary action for transporting liquid and a low thermal resistance to vapor evolution for improved evaporation and transport compared to conventional wick geometries. Therefore, nanostructured bristle wicks enable more efficient heat exchange in a heat pipe.

[0006] The wick structure must accommodate two physical behaviors in the heat pipe. At the evaporator, a low thermal resistance is required, while to transport the liquid from the condenser through the adiabatic region and back to the evaporator, a high capillary pumping pressure is desired. This can lead to heat pipes with hybrid or composite wicks to accommodate these two regions. In the present invention, this can be accomplished by engineering nanowires of different dimensions in the two areas of relevance.

SUMMARY OF THE INVENTION

[0007] The heat pipe wicking material is shown schematically in FIG. **2**. The device has many of the same attributes of larger heat pipe structures. The device comprises a metallic enclosure with a wick material on its inner walls. In the preferred embodiment, the wick comprises an array of substantially vertically aligned copper nanowires extending out from the walls of the enclosure. The wires are between 10 and 400 nm in diameter, spaced at 20 to 600 nm and are up to approximately 250 microns in length. SEM micrographs of copper nanowire arrays that can be used for the wick application are also shown in FIGS. **6** and **7**. The wick performs similarly to conventional wicks in that capillary action is used as the mechanism to pump a working fluid to the evaporator. Heat is extracted from the device to be cooled, typically an electronic device, through evaporation of the working fluid. Vapor condensing on the cold (condenser) side of the heat pipe deposits the heat for further dissipation by a conventional convection heat sink or for transfer to another heat pipe in the thermal bus.

[0008] The significant advantage possessed by the nanowire device is that the boiling surface area available in the nanowire array can be well in excess of 1000 cm^2 per square centimeter of the surface area of the heat pipe surface that it occupies. This is to be compared with boiling surface areas of only a few cm^2 per cm^2 in grooved heat pipes and a few tens of cm^2 in sintered metal powder devices. This enhancement to the surface area can potentially result in a several fold improvement in heat flux transport enabling devices that can remove up to several hundred W/cm^2.

[0009] Nanobristle arrays (shown schematically in FIG. **2**) have significant attributes that make them advantageous as the wick material in heat pipes. The tight packing of the bristles in the array provides a high capillary pressure to promote fluid flow through the wick while the aligned array configuration of the bristles provides a clear path for vapor to escape. Thus the nanobristle architecture can significantly decrease the thermal resistance and increase the fluid flow compared to currently used sintered powder copper, screen, or axially grooved wicks. These two attributes of the nanobristle array improves the heat flux capacity of heat pipe devices to greater than 300 W/cm^2. Heat fluxes of approximately 25 W/cm2 to 125 W/cm2 with a thermal resistance less than 0.06° C.-cm^2/W , have been observed.

[0010] The nanobristle array wick allows the height, or profile, of the entire heat pipe to be reduced to less than 1 mm (0.040") and can be used where conventional heat pipe devices and cooling technologies are inadequate. This is critical for portable electronic devices that utilize ever increasingly powerful (heat generating) processors in smaller and smaller packages. FIG. **3** schematically shows a thermal bus architecture utilizing nanobristle heat pipe technology as the key link between the high power circuits and the external thermal bus.

[0011] The current heat pipe technology typically limits the wicking structure to a minimum thickness of 1 mm to provide adequate cooling. Thus, the heat pipe has to be greater than about 2 mm thick, plus packaging, plus evaporation space. Typically, 5 mm in width is a minimum dimension. To get any smaller, the wicking structure has to be smaller. The current invention can be used to create wicking structures that are only about 50-100 microns (10× improvement) in bristle wick length, thus making it possible for a 300 micron width copper layer sufficient to enclose the heat pipe volume while still providing the same heat transport capacity. The invention permits a heat pipe with a 900 micron cross section or less. This reduces weight and size for the same amount of heat transfer efficiency. In addition to improvements in weight and size, the nano-structured wicking material exhibits improved capillary action and lower thermal resistance. The bristle structures are arrayed. The bristles have a uniform size and spacing that can be controlled to optimize the capillary action and thermal resistance for a particular application. A 35% to 50% reduction in thermal resistance than sintered copper powder wicks can be achieved by means of the use of nanostructured wicking materials. Sintered copper powder is the industry preference and currently exhibits the lowest thermal resistance of all currently commercially distributed heat pipe wick structures.

[0012] Other key features of the nanowire array heat pipe are that it can be built with an extremely thin profile and that the nanowire wick will enable operation at any orientation. Devices less than 1 mm thick can be built that can be directly incorporated into high power component packages. This design flexibility can enable the top of the heat pipe to be specifically designed to incorporate a coupling structure so that the device can be efficiently mated to a thermal (heat pipe) bus as well as the device to be cooled.

PRIOR ART

[0013] Heat pipes are well known heat transfer devices that are highly useful for heat management in electronic devices and packaging. Heat pipes are disclosed in a number of U.S. patents, including U.S. Pat. No. 3,952,798, issued on Apr. 27, 1976, which is incorporated herein by reference for all that it teaches.

[0014] Other references attempt to improve the wicking material that provides the capillary action within the device for moving the liquid phase of the heat transfer fluid.

[0015] U.S. Pat. No. 7,086,454, which is hereby incorporated by reference, discloses the use of fiber bundles as a wick.

[0016] U.S. Pat. App. No. 20060207750A1 which is hereby incorporated by reference, discloses the notion of two kinds of wick, one for the evaporator and the other for the condenser side of the device.

[0017] U.S. Pat. App. No. 20050116336A1 which is hereby incorporated by reference, discloses the use of nanostructured material, but as an additive to bulk materials in order to improve their heat conduction. The actual devices presented are not heat pipes, but heat sinks.

[0018] U.S. Pat. App. No. 20060016580A1 which is hereby incorporated by reference, discloses the use of sintered powder, which is not novel. The disclosure notes that voids in the resulting wick are on the order of nanometers in size. However, this approach does not produce a regular structure, rather the pattern that voids create are result of how the powder particles attach to each other during sintering.

[0019] U.S. Pat. No. 6,427,765, which is incorporated herein by reference, discloses a woven wire wick for a heat pipe.

[0020] U.S. Pat. No. 4,109,709, which is incorporated herein by reference, discloses glass fibers with grooves as a wicking structure for a heat pipe.

[0021] U.S. Pat. No. 4,274,479, which is incorporated herein by reference, discloses the use of grooves laid into the sintered powder wick.

[0022] U.S. Pat. No. 4,015,659, which is incorporated herein by reference, discloses the use of metal whiskers as the wick.

[0023] An Introduction to Heat Pipes, G. P. Paterson, John Wiley & Sons, New York, 1994 is hereby incorporated by reference for all that it teaches.

[0024] Attempts continue to improve the heat flux capacity of heat pipes by means of adjusting the composition of the wicks. See "I. Sauciuc, M. Mochizuki, K. Mashiko, Y. Saito and T. Nguyen, Proceedings of the Sixteenth IEEE SEMI-Therm Symposium, Anaheim, Calif., USA, 2000 pp. 27-32.

BRIEF DESCRIPTION OF THE DRAWINGS

[0025] FIG. **1**. Schematic representation of the heat pipe thermal cycle heat transfer mechanism.

[0026] FIG. **2**. Diagram of a nanobristle array.

[0027] FIG. **3**. Electronic systems thermal management concept utilizing nanobristle wick heat pipes. The inset is an SEM image of copper nanobristles.

[0028] FIG. **4**. Schematic of porous anodized aluminum oxide on a copper substrate. The spacing between channels, the channel diameter and the channel depth are all controllable parameters.

[0029] FIG. **5**. Plot of current vs. time for the formation of the alumina nanochannels. The increase in current corresponds to the nanochannels reaching the copper substrate.

[0030] FIG. **6**. SEM image of copper nanobristles attached to a copper substate and formed from aluminum clad onto a copper substrate.

[0031] FIG. **7**. SEM image of copper nanobristles formed using an Anodisc filter template held onto a copper substrate.

[0032] FIG. 8. Thermal Resistance vs. Input Heat Flux for heat pipes with nanobristle array wicks. Broken line is published data for sintered powder heat pipes tested under the same conditions.

[0033] FIG. 9. Reflectivity inspection for missing nanobristles in the nanobristle array. A rastering laser and photodiode can be used to find patches of missing bristles on a continuously moving nanobristle wick sheet

[0034] FIG. 10. UV-Visible spectrum of copper nanobristle array. The two absorption bands are due to the localized surface plasmon resonance.

[0035] FIG. 11. Illustrated comparison of fluid flow in nanowire and sintered powder heat pipe wicks

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0036] Performance data for tested nanowire wicks are shown in FIG. 8. The data clearly show that the nanowire materials can sustain heat fluxes in excess of 100 W/cm^2 with a 35% reduction in thermal resistance. Typical computer applications today have heat fluxes of 100-200 W/cm^2 yet the high thermal resistance of conventional heatpipes do not provide the proper temperature (cooling) for optimal performance. Further, the materials, although using a much lower volume (~100 micron thick) than the competing sintered powders (~1 mm thick), have superior heat flux performance

[0037] Nano-bristle arrays are grown on a substrate by the use of a template. In the preferred embodiment, the template is formed using an anodization process in order that a regular set of pores are formed that are fully open to the substrate surface. A polymer resist layer coats the back side of the substrate. The substrate, with the polymer and template layers attached is then bathed in a solution that deposits a substance in the pores. Finally, the template layer and polymer layer are removed. The result is the substrate with substantially vertical bristles comprised of the substance appended on one side. The dimension and spacing of the bristles is determined by the pore dimensions and spacing in the template. The substrate and substance may be the same material, preferably copper. The template is preferably aluminum oxide and the resist a polymer resist coating. The anodization of aluminum metal to form a porous aluminum oxide layer is well established, in the articles listed here, and each is incorporated herein by reference for all that they teach:

[0038] F. Keller, M. S. Hunter, and D. L. Robinson, Journal of the Electrochemical Society 100, 411-419 (1953)

[0039] O. Jessenky, F. Muller, and U. Gosele, Applied Physics Letters 72, 1173-1175 (1998).

[0040] G. E. Thompson and G. C. Wood, Nature 290 230-232 (1981).

[0041] The first method for producing the nanobristle array uses a thin sheet (30-80 μm thick) aluminum overlaid on a 1 mm thick copper sheet. The copper is first covered with a polymer film (Coscoat 4560 supplied by General Chemical Corporation) to protect the copper during anodization. Anodization of the Aluminum metal is then performed resulting in the growth of porous alumina in which the diameter, depth, and spacing of the nanochannels can be controlled by varying the electrical parameters and chemical concentrations used in the anodization process. Controlling the dimensions of the self-assembled porous template is important for engineering the desired characteristics of the nanobristle wick material. A schematic of anodized Al on Cu is shown in FIG. 4.

[0042] Metallic nanowires can be produced using an aluminum oxide template, are also disclosed in the articles listed in the following list, and each is incorporated herein by reference for all that they teach:

[0043] D. Al-Mawlawi, C. Z. Liu, and Martin Moskovits Journal of the Materials Research Society, 9, 1014-1018 (1994).

[0044] N. J. Gerein and J. A. Haber, Journal of Physical Chemistry B, 109, 17372-17384, (2005).

[0045] The preferred embodiment uses alumina as the template and copper as both the substrate and the bristle. The method of forming is as follows:

1. The starting material is a metallic substrate with copper being the preferred embodiment due to it's high thermal conductivity. The substrate material can be any electrically conducting substrate. The substrate is first cleaned

2. Form an aluminum cladding layer on the substrate. The aluminum layer thickness is such that when anodized, the oxide layer will be as deep or deeper than the desired length of the nanobristles. Other materials may be used as cladding, including titanium, silicon, zinc, zirconium, lanthanum, niobium, tungsten, tin, indium, strontium, vanadium, molybdenum, calcium, or blends of two or more, and their oxides. In fact, any metal that can produce a porous oxide may be used. Aluminum is preferred because it's oxide produces ordered pores and it is relatively inexpensive in order to define pore size and spacing. The formation step has the following sub-steps:

a. Clean Aluminum cladding. This can be done using standard laboratory solvents. Further, for some applications requiring high uniformity, the aluminum can be electropolished.

b. Bake in the presence of oxygen for the initial formation of an Al_2O_3 layer. This is a non-porous layer. Typically, the initial oxidization should produce a layer of oxide on the cladding of about 20 to about 100 nm in depth. The temperature can range from about 100 to about 450° Celsius and for times from about 1 to about 240 minutes. All references to "degrees" means degrees Celsius, not Fahrenheit.

3. Coat the copper substrate with an insulator, e.g. a polymer to prevent anodization on the backside of the copper substrate and to protect the surface from corrosion. One example is a material called Coscoat from General Chemical Corporation, Detroit Mich. Other materials include polyimide, Teflon, nail polish, polyethelene, or a silicon based resin.

4. Anodize the Aluminum. This step converts the Aluminum metal cladding to Aluminum Oxide. As oxide forms it creates the pores. The pores form because of a lattice size mismatch between the bulk Al and Al_2O_3 and other thermodynamic considerations. In other words, the atomic spacing of the Aluminum atoms in bulk is not the same as the spacing between the Al_2O_3 molecules, so regular voids begin to form along the surface. These voids work down toward the surface of the substrate forming pores in the oxide layer. The pores self assemble into a quasi-hexagonal matrix structure. The pore diameters are a function of the anodization conditions (voltage, electrolyte, cathode geometry), while the depth is a linear function of anodization time. The voids form because the law of thermodynamics makes the anodization uneven and as a result the voids becomes pores. It is possible to use micro-lithography techniques to define the surface of the aluminum before anodization. The sub-steps are as follows:

a. Anodization bath: In the preferred embodiment, about 0.3 weight % oxalic acid is used, but other bath solutions may be used, including sulfuric acid, phosphoric acid, chromic acid and mixtures of them. By changing electrolyte bath type and concentration, and the voltage, one can adjust size of the pores. In a representative anodization process of Al clad onto copper, the Al layer is anodized in a solution of about 0.3-wt % oxalic acid at about 2° C. The anodization is carried out until all the Al metal is consumed and the channels in the Al_2O_3 penetrate through to the copper. This takes about 12-to about 72 hours depending on the thickness of the Al. Anodization is performed at about 20 to about 200 V dc depending on the desired pore diameter and spacing. As the Al_2O_3 pores begin to penetrate the Al/Copper interface, the anodization current begins to increase.

[0046] Nanobristle arrays using porous Al_2O_3 as a template have been successfully engineered using electrodeposition of Cd, Fe, Au, Ag, Cu, Ni, and other metals from aqueous solution, as further disclosed in the articles listed in the following and incorporated herein by reference: Y. Peng, H. Zhang, S. Pan, and H. Li, Jour. Appl. Phys. 87, 7405 (2000) and A. Jansson, G. Thornell, and S. Johansson, J. Electrochem Soc., 147, 1810 (2000)

b. Anodization is stopped immediately when the pores reach the copper. The method used is to measure the anodization current and when it spikes, it means the pores have reached all the way through to the copper substrate. When the current reaches about 2 to about 3 times its steady state value, this indicates that the Al metal has been consumed and the anodization process is stopped. A computer or other electronic device may be used to stop the current when the spike is detected.

c. Following anodization, the pores can be widened and remnant Al_2O_3 cleared from the bottom of the pores at the copper interface in an about 5 to about 25 wt % solution of phosphoric acid. This also cleans the copper surface. Once the template is formed, metal is electroplated into the pores to form nanobristles. As discussed above, other acids may be used.

6. Grow the Bristles in the Pores. In the preferred embodiment, electroplating is used to deposit copper in the pores. The copper substrate is placed in a copper sulfate bath, with an electric current that causes electroplating in the pores. Other metals may be deposited that are different from the substrate. The sub-steps are as follows:

a. The electroplating current and voltage are about 0.75 volts, about 200 milliamps of current up to about 600 milliamps. The copper plating bath is commercially available from Transene Co. named acid-copper electroplating bath.

8. Etch the Template. The Aluminum Oxide is removed from the substrate by bathing the device in Phosphoric acid at about 37 degrees plus or minus 10, degrees, 5% by weight, plus or minus 2%. It is possible to use other etching acids or bases such as NaOH, HCl, H_2SO_4, HF, as described above and further including hydrochloric acid. It is also possible to use bases to etch, including sodium hydroxide.

9. Remove the polymer coating. Any typical solvent may be used to wash the polymer coating off the device. In some cases, the polymer may be peeled away.

[0047] A key step in developing an automated production process is the detection of the point where the aluminum metal is completely oxidized and the oxide layer of pores reaches the copper base. If the anodization is continued past the interface, the copper will anodize leaving a material unsuitable for heat pipe applications. FIG. **5** is a plot of current vs. time for the anodization process. When the aluminum is completely consumed and the pores reach the copper base the current increases dramatically. For the production of nano bristle wicks a breaker was included in the circuit which opened when the current increased stopping the anodization process. A computer controlled current monitoring process more appropriate for manufacturing is typically used to stop the anodization at the correct point.

[0048] Following the formation of the nanobristles the alumina template (alumina clad on copper or the Anodisc filter) is removed by etching in 1 M NaOH. FIG. **6** shows an SEM micrograph of copper nanobristles formed from aluminum clad on copper. In the preferred embodiment, the resulting nanobristles range in diameter from 100-250 nm with a height of 30-70 μm and a separation of 75-200 nm depending on the anodization conditions. FIG. **7** shows an SEM image of a nanobristle array prepared by using an Anodisc filter. The nanobristles had diameters ranging from 150-300 nm, lengths of 2-7 μm and spacing of 90-220 nm. In the test case, the nanobristle wick comprised the base of the heat pipe where a heating element was mounted. That is, the wick can be formed on a substrate that is then attached to the body of the heat pipe, with the bristles pointed into the cavity of the heat pipe. Alternatively, the body of the heat pipe can be treated and the nanowires grown directly on the surface.

[0049] Heat transport data were measured on prototype heat pipes one inch in diameter. Nanobristle array wicks gave evaporator thermal resistance values ranging from 0.06 to 0.08° C.-cm2/W within the desired heat flux working range of 100-200 W/cm2. The heat pipe evaporator is the primary source of thermal resistance in a heat pipe. The nanobristle array wicks show a significant 25-30% reduction in thermal resistance over the sintered copper powder wicks. Sintered copper powder is currently used as the wicking material in a large percentage of heat pipe applications where improved performance is desired.

[0050] The heat flux capacities obtained for the prototypes provide the required capacities for the current Hewlett Packard and AMD chip packages (80-100 W/cm2) and new generation microprocessors such as the Intel Pentium 4 Extreme Edition (150 W/cm2). The thermal resistances measured for the nanobristle wicks were 25-30% lower than current sintered copper heat pipes. This improvement in thermal resistance coupled with the low profile (<100 μm compared to ~1 mm for sintered copper) is very attractive for the production of new heat pipes.

[0051] Techniques have been developed for monitoring the uniformity of the nanobristle arrays. In the first method a prototype nano-bristle wick inspection system (shown schematically in FIG. **9** measures the reflectivity of the surface at one wavelength as an indication of the array uniformity. There is a pronounced plasmon resonance effect due to the size of the wires. If there are patches in the array that lack bristles, the reflectivity will be high as shown in FIG. **10**. It is anticipated that longer more densely packed bristles will lead to a decrease in reflectivity due to light being trapped in the nanobristle matrix or diffused by reflecting from the nanobristle surfaces.

[0052] The light source can also be a laser or a UV-Visible light source, adding a monochromator and replacing the detector with a CCD array detector to allow for the collection of real time reflectance spectra of the nanobristle array surface as it is scanned. UV-Visible spectra give direct information about the plasmonic features of copper nanobristle arrays. FIG. **10** shows a spectrum for a copper nanobristle array. Two bands are observed in the spectrum at ~314 and 413 nm. These bands correspond to the transverse and longitudinal localized surface plasmon resonances of the nanobristle array for that size of nanowire. Changes in the dimensions of the nanobristles in an array result in changes in the spectrum. This provides a mechanism for monitoring the uniformity of the nanobristle arrays. The advantage over the laser technique is that the entire spectrum can be obtained which will provide more details about the array surface.

[0053] Unlike its sintered powder counterpart, the nanowire wick has anisotropic flow characteristics. The flow channels through the wick are narrow in the plane of the device, but are long normal to the substrate surface. The capillary pressure should be high as the high surface area provides high surface tension. The flow resistance in the plane of the wick may be low, however, since the net channel cross-section can be as high as 10 micron for 100 micron wires spaced 100 nm apart. This is nearly comparable to the channel cross-section in sintered powder wicks made of 15 micron particles. Flow normal to the plane of the nanowire device will be unimpeded as illustrated in FIG. **11**. This provides a significant advantage as convection currents in the working fluid will easily circulate to the vapor chamber, potentially minimizing bubble formation. The potential combination of these characteristics in the nanowire wick can result in a device with unprecedented thermal performance.

[0054] The two primary design parameters for copper/water heat pipes are the heat transport capability and the thermal resistance. First, the heat transport capability is dependent on the pore radius and permeability of the wick structure. An ideal heat pipe wick would have a small pore radius, providing good capillary pumping, and a high permeability, allowing liquid and vapor to easily pass through the wick. Grooved wicks have a large pore radius and high permeability so that they can transport large heat loads in a horizontal or gravity aided position but do not function well against gravity or other forces of acceleration. Sintered metal powder wicks have small pore radii giving good capillary pumping, leading to the ability to transfer large heat loads against gravity, but with relatively low permeability. The second design consideration for heat pipes is thermal resistance. It is desirable to have a low heat pipe thermal resistance. The thermal resistance is a function of heat pipe geometry, wick structure, condenser length, evaporator length, and working fluid.

[0055] The working fluid used in a heat pipe, as well as the material the wick and package are made of depend on the relative operating temperature of the device. These can be divided into three general classes: Cryogenic (10-150° K) Low Temperature (150-750° K) and High Temperature (750-5000° K). Most heat pipe applications for electronics thermal management require working fluids with boiling points between 250-375° K thus limiting the choice of working fluids to ammonia, acetone, methanol and water or dielectrics such as Freon. Cryogenic application utilize liquid H_2, O_2, or N_2, while high temperature applications typically utilize liquid metals such as Mercury, Potassium, Sodium, Lithium or Silver. In the preferred embodiment here electronic cooling application are targeted with water most often used as the working fluid.

[0056] Close packed nanowire arrays are desirable for the evaporator but may not provide the ultimate capillary pumping. Thus, nanowires with larger spacing can be used for the condenser and adiabatic transport sections of the heat pipe in a graded hybrid nanowire structure where the nanowire packing is sparse at the condenser end becoming tightly packed at the evaporator. It is clearly established that the vertical alignment of the nanowires decreases thermal resistance at the evaporator. However, also due to their small size, patterning of the nanowires where they don't coat the entire surface of the inner-wall may also dramatically improve the capillary pumping characteristics. This can be achieved by simply depositing the nanowire template selectively, so that the nanowires have grooves, a cross pattern, triangles or other shapes providing either connecting or separated spaces on the heat pipe inner wall where there are no nanowires in between the parts of the wick that do have a nanowire array coating.

[0057] Practitioners of ordinary skill will recognize that different sized nanostructures, including nanowires can be used at the evaporator, condenser, and return path regions of the heat pipe. In the same way, different wick materials could be used to feed the working fluid to the nanowires at the evaporator. For example, a conventional wick could be hybridized with the nanowire wick, either selectively or patterned throughout the inner wick structure of the heat pipe. In this way, a sintered powder wick can be used in one part of the pipe while the nanostructure wick is used in another.

[0058] One can define a boiling surface area ratio (BSR) to be equal to the effective per unit surface area with the wicking material for evaporation divided by the unit area that the wicking material occupies along the interior surface of the heat pipe. For the nanowire array, we can calculate the BSR as follows:

C=Nanowire Center to Center Spacing, D=Nanowire Diameter, L=Nanowire Length $BSR=\pi DL/C^2$ if the Nanowire Tip area is negligible.

Case #1: if C=20 nm, D=10 nm, L=1 μm, BSR=125.6

Case #2: If C=250 nm, D=200 nm, L=100 μm, BSR=1962.5

Case #3: If C=100 nm, D=60 nm, L=200 μm, BSR=3600

[0059] In this case, BSR is calculated based on only the outer cylindrical area of the nanowires.

For case #2, on a 1 cm piece of material, the nanowire tips occupy about 0.50 cm^2, justifying their exclusion from the calculation.

[0060] By lengthening the nanowires and placing them on narrower spacing one can get the BSR up to approximately 3,600, that is, Case #3. Typical sintered metal powder wicks exhibit a BSR of about 35. The wicking material disclosed in U.S. Pat. No. 4,015,659 discloses a material with a BSR estimated to be approximately 5 to approximately 50, depending on a range of whisker length of 100 microns to 1 millimeter. Practitioners of ordinary skill will recognize that if the length of the nanowire is too long relative to its diameter, then it is more likely to crack or otherwise fail. In the preferred embodiment, the aspect ratio of the nanowires should be less than approximately 2500 to 1. The aspect ratio is defined to be the cross sectional distance of the nanowire, i.e. its diameter, divided by its length. The optimal ratio is dependent on a number of factors besides diameter and includes how closely packed the wires are. Although the wires are intended to be free standing, and are indicated as that schematically, in practice the wires lean against each other somewhat, which improves their ability to support longer nanowires. As a result, they are substantially free standing nanowires, meaning that the trajectory of their growth is as separated wires, although at the end of the process there is some touching among them. Practitioners of ordinary skill will also recognize that the preferred embodiment produces nanowires that are substantially round in cross section. However, other methods may be used to create other cross sectional shapes, depending on crystal structures, pore shape and other parameters. Therefore, where the dimension "diameter" is referred to, this does not limit the dimension to a circular cross section, but rather also applies to non-circular cross sectional dimension.

[0061] The point of this invention is that the nanowires form a wicking structure whose BSR on a per-wick thickness basis is very high, where in this case, the wick thickness is essentially the height of the nanowires. In other words, there is more boiling surface in a thinner wick. To normalize for wick thickness, the BSR can be divided by the thickness of the wick in microns, or BSR/t. The typical application of this invention exhibits a BSR/t on a range of approximately 18 to 125, corresponding to cases 1, 2 and 3 above. Meanwhile, the sintered metal powder example assumes a 1 mm thick coating and thus has a BSR/t calculated to be about 0.035. The metal whisker approach has a higher BSR/t than the sintered powder, calculated to be about 0.054. These prior art materials exhibit a BSR on the order of 3 to 5 for wick thicknesses of 100 microns.

[0062] The described embodiments of the invention are intended to be exemplary and numerous variations and modifications will be apparent to those skilled in the art. All such variations and modifications are intended to be within the scope of the present invention as defined in the appended claims

Although the present invention has been described and illustrated in detail, it is to be clearly understood that the same is by way of illustration and example only, and is not to be taken by way of limitation. It is appreciated that various features of the invention which are, for clarity, described in the context of separate embodiments may also be provided in combination in a single embodiment. Conversely, various features of the invention which are, for brevity, described in the context of a single embodiment may also be provided separately or in any suitable combination. It is appreciated that the particular embodiment described in the Appendices is intended only to provide an extremely detailed disclosure of the present invention and is not intended to be limiting.

[0063] The spirit and scope of the present invention are to be limited only by the terms of the appended claims.

What is claimed:

1. A heat pipe with an interior surface enclosing a cavity comprised of at least one wicking material residing within said cavity, said wicking material comprised of a plurality nanowires.

2. The heat pipe of claim **1** where the cross sectional dimension of at least one of the plurality of nanowires are between approximately 10 nanometers and approximately 400 nanometers.

3. The heat pipe of claim **1** where the diameter of at least one of the plurality of nanowires are between approximately 50 nanometers and approximately 250 nanometers.

4. The heat pipe of claim **1** where the plurality nanowires are substantially spaced apart between approximately 20 nanometers center to center and approximately 600 nanometers center to center.

5. The heat pipe of claim **1** where the plurality nanowires are substantially spaced apart between approximately 75 nanometers center to center and approximately 500 nanometers center to center.

6. The heat pipe of claim **2** with the limitations of claim **4**, where the diameter of the nanowire is at least equal to the center to center spacing.

7. The heat pipe of claim **3** with the limitations of claim **5**, where the diameter of the nanowire is at least equal to the center to center spacing.

8. The heat pipe of claim **1** where the length of at least one of the nanowires is between approximately 100 nanometers and approximately 250 microns.

9. The heat pipe of claim **1** where the length of at least one of the nanowires is between approximately 50 microns and 150 microns.

10. The heat pipe of claim **1** where the length of the nanowires are between approximately 1 micron and approximately 250 microns, the spacing of the nanowires is between approximately 20 nanometers center to center and 600 nanometers center to center and the diameter of the nanowires is between approximately 10 nanometers and 400 nanometers, where the diameter of the nanowire is at least equal to the center to center spacing and the aspect ratio of the wire is no more than approximately 2500 to 1 and is at least 1 to 1.

11. The heat pipe of claim **10** where the length of the nanowires are between approximately 50 microns and approximately 150 microns.

12. The heat pipe of claim **10** where the cross section dimension of the heat pipe, measured substantially perpendicularly to the axis along which the vapor flows, is between approximately 500 microns and two millimeters.

13. The heat pipe of claims **1** and **10** where the nanowires are substantially free standing.

14. A heat pipe comprised of at least one wicking material that is comprised of nanostructures, where the wicking material has a thermal resistance less than approximately 0.08° C.-cm2/W when the heat flux is between approximately 100 W/cm2 and approximately 200 W/cm2.

15. A heat pipe comprised of at least one wick, where the wick is comprised of nanostructred material with anisotropic flow characteristics whereby the resistance to fluid flow along the longitudinal axis of the pipe is substantially higher than the fluid flow approximately normal to the interior surface of the heat pipe that the wick material is adjacent to,

16. A heat pipe of claim **1**, **2**, **3**, **4**, **5**, **6**, **7**, **8**, **9**, **10**, **11**, **12**, **13** or **14** where the nanowire wicking material occupies at least one selected region along the interior surface of the heat pipe, said region being an area that is less than the interior surface in area.

17. The heat pipe of claim **16** where the selected region is one of a groove, a cross pattern, a trianglular grid, a mesh.

18. The heat pipe of claim **16** where the selected regions are a substantially repeating pattern across the interior surface.

19. A heat pipe of claim **1** where the nanowire wicking material for the region that is substantially evaporating the heat transfer fluid has different nanowire dimensions than the wicking material in the region that is substantially condensing the heat transfer fluid.

20. A heat pipe of claim **19** where the wicking material in the condensing region is not a nanostructure wicking material.

21. A method of forming a heat pipe body comprised of an interior surface enclosing an interior cavity, comprised of: growing nanowires on a substrate; attaching the substrate to a heat pipe body with the nanowires facing the interior cavity of the heat pipe.

22. The method of claim **21** comprising growing the nanowires through a template attached to the substrate, said template having at least one pore that substantially penetrates through the template to the surface of the substrate.

23. Method of claim **22** further comprising anodizing a metallic layer to create the template.

24. The method of claim **23** where the metallic layer is aluminum.

25. The method of claim **23** where the template is Aluminum Oxide.

26. The method of claim **23** where the anodized metallic layer is one of: Titania, Silica, Zinc Oxide, Zirconium Oxide, Lanthinum Oxide, Niobium Oxide, Tungsten Oxide, Tin Oxide, Indium Oxide, Indium Tin Oxide, Strontium Oxide, Vanadium Oxide, Molybdinum Oxide, Calcium/Titanium Oxide, blends of such materials.

27. The Method of claim **23** further comprising detecting a substantial spike in anodization current and shutting off the anodization current as a result of such detection.

28. The method of claim **27** where the shutting off occurs as a result of the anodization current spike being between approximately 2 and approximately 3 times its substantially prior steady state value.

29. The method of claim **21** further comprising characterizing the surface of the substrate where the nanowires have been grown by reflecting light energy off the surface and detecting at least one spectral characteristic of the reflected light.

30. The method of claim **29** where the spectral characteristic is detecting the amplitude of reflected light to incident light at approximately the wavelength of the two modes of plasmon resonance in the nanowires.

31. The method of claim **22** comprising growing nanowires within the at least one pore in the template by means of electroplating a metal.

32. The method of claim **31** where the electroplating current is in the range of approximately 200 milliamps to approximately 600 milliamps.

33. The method of claim **31** where the electroplating voltage is approximately 0.75 volts.

34. The method of claim **31** where the metal is copper.

35. The method of claim **31** where the metal is comprised of one of Cd, Fe, Au, Ag, Ni or Molybdinum.

36. The method of claim **31** further comprising etching the template.

37. The method of claim **36** where the etch solution is one of Phosphoric acid, NaOH, HCl, H2SO4, HF, Sodium Hydroxide.

38. The method of claim **22** where an Anodisk filter is the template.

39. A heat pipe comprising at least one wicking material, where the at least one wicking material occupies a region on the surface of the interior of the cavity of the heat pipe, where the boiling surface ratio of the wicking material is between approximately 125 and approximately 3600.

40. A heat pipe comprising at least one wicking material, where the at least one wicking material occupies a region on the surface of the interior of the cavity of the heat pipe, where the boiling surface ratio of the wicking material is greater than approximately 125 and less than approximately 1962.

41. The heat pipe of claim **39** where the boiling surface ratio divided by the thickness of the wicking material measured in microns is between approximately 18 and approximately 125.

42. The heat pipe of claim **39** where the boiling surface ratio divided by the thickness of the wicking material measured in microns is between approximately 1500 and 2500.

43. The heat pipe of claim **39**, **40**, **41** or **42** where the wicking material is nanostructured.

44. The heat pipe of claim **43** where the nanostructures are an array of nanowires.

45. A method of forming a heat pipe body comprised of an interior surface enclosing an interior cavity, comprised of: growing nanowires on at least one region of the interior surface.

46. The method of claim **45** comprising growing the nanowires through a template attached to the interior surface, said template having at least one pore that substantially penetrates through the template to the surface of the interior surface.

47. Method of claim **46** further comprising anodizing a metallic layer to create the template.

48. The method of claim **47** where the metallic layer is aluminum.

49. The method of claim **47** where the template is Aluminum Oxide.

50. The method of claim **47** where the anodized metallic layer is one of: Titania, Silica, Zinc Oxide, Zirconium Oxide, Lanthinum Oxide, Niobium Oxide, Tungsten Oxide, Tin Oxide, Indium Oxide, Indium Tin Oxide, Strontium Oxide, Vanadium Oxide, Molybdinum Oxide, Calcium/Titanium Oxide, blends of such materials.

51. The Method of claim **47** further comprising detecting a substantial spike in anodization current and shutting off the anodization current as a result of such detection.

52. The method of claim **51** where the shutting off occurs as a result of the anodization current spike being between approximately 2 and approximately 3 times its substantially prior steady state value.

53. The method of claim **45** further comprising characterizing the surface of the substrate where the nanowires have been grown by reflecting light energy off the surface and detecting at least one spectral characteristic of the reflected light.

54. The method of claim **46** where the spectral characteristic is detecting the amplitude of reflected light to incident light at approximately the wavelength of the two modes of plasmon resonance in the nanowires.

55. The method of claim **46** comprising growing nanowires within the at least one pore in the template by means of electroplating a metal.

56. The method of claim **55** where the electroplating current is in the range of approximately 200 milliamps to approximately 600 milliamps.

57. The method of claim **55** where the electroplating voltage is approximately 0.75 volts.

58. The method of claim **55** where the metal is copper.

59. The method of claim **55** where the metal is one of Cd, Fe, Au, Ag, Ni, Mb.

60. The method of claim **55** further comprising etching the template.

61. The method of claim **60** where the etch solution is one of Phosphoric acid, NaOH, HCl, H_2SO_4, HF, Sodium Hydroxide.

62. The method of claim **55** where an Anodisk filter is the template.

63. A method of making a heat pipe comprised of a body and an interior cavity, comprising:

Cladding a substrate comprised of a first metal with a second metal;

Oxidizing the second metal by means of anodization whereby the oxide forms pores;

Electroplating a third metal within the pores to form nanowires;

Etching the oxide of the second metal, whereby the nanowires become substantially free-standing;

Attaching the substrate to the heat pipe body such that the nanowires are inside the interior cavity of the heat pipe.

64. A method of making a heat pipe comprised of a metallic body comprised of a cavity with an interior surface comprising:

Cladding a region on the interior surface with a second metal;

Oxidizing the second metal by means of anodization whereby the oxide forms pores;

Electroplating metal within the pores to form nanowires;

Etching the metallic oxide, whereby the nanowires become substantially free-standing.

65. A heat pipe comprising at least one wicking material, where the at least one wicking material is nanostructured and occupies a region on the surface of the interior of the cavity of the heat pipe, where the boiling surface ratio of the wicking material is between approximately 125 and approximately 3600.

66. A heat pipe comprising at least one wicking material, where the at least one wicking material is nanostructured and occupies a region on the surface of the interior of the cavity of the heat pipe, where the boiling surface ratio of the wicking material is greater than approximately 125 and less than approximately 1962.

67. The heat pipe of claim **66** where the boiling surface ratio divided by the thickness of the wicking material measured in microns is between approximately 18 and approximately 125.

68. The heat pipe of claim **65**, **66** or **67** where the nanostructured wicking material is comprised of a plurality of nanowires, where the nanowires are between approximately 1 micron and approximately 250 microns in length.

69. The heat pipe of claim **68** where the cross section dimension of the heat pipe, measured substantially perpendicularly to the axis along which the vapor flows, is between approximately 500 microns and two millimeters.

70. The heat pipe of claim **68** where the nanowires are free standing and substantially regularly spaced.

71. A method of cooling electronic devices using a nanostructured heat pipe comprised of conducting heat generated by said device into a wicking material comprised of a nanowire array substantially surrounded by a fluid and evaporating said fluid.

72. The method of claim **71** where the nanowire array is comprised of a plurality of nanowires, where the length of the nanowires are between approximately 1 micron and approximately 250 microns, the spacing of the nanowires is between approximately 20 nanometers center to center and 600 nanometers center to center and the diameter of the nanowires is between approximately 10 nanometers and 400 nanometers, where the diameter of the nanowire is at least equal to the center to center spacing and the aspect ratio of the wire is no more than approximately 2500 to 1 and greater than 1 to 1.

73. The method of claim **72** where the length of the nanowires are between approximately 50 microns and approximately 100 microns.

74. The method of claim **72** where the cross section dimension of the heat pipe, measured substantially perpendicularly to the axis along which the vapor flows, is between approximately 500 microns and two millimeters.

75. The method of claim **71** where the nanowires are substantially free standing.

76. The heat pipe of any of claims **1** through claim **15** where the spacing of the nanowires is graded so that it is relatively sparse in the condenser region and more tightly packed in the evaporator region.

77. The method of any of claims **21** through **26** or **45** through **49** where the nanowire growth occurs on selected regions.

78. The method of any of claims **21** through **26** or **45** through **49** further comprising using microlithography techniques to change the surface profile of the metal to be anodized prior to anodization.

79. The heat pipe of any of claims **1** through claim **15** where the nanowires are substantially regularly spaced.

80. The heat pipe of any of claims **1** through claim **15** where the nanowires are substantially oriented substantially normal to the plane of the substrate.

81. The heat pipe of claim **44** where the nanowire array is comprised of a plurality of nanowires, where the length of the nanowires are between approximately 1 micron and approximately 250 microns, the spacing of the nanowires is between approximately 20 nanometers center to center and 600 nanometers center to center and the diameter of the nanowires is between approximately 10 nanometers and 400 nanometers, where the diameter of the nanowire is at least equal to the center to center spacing and the aspect ratio of the wire is no more than approximately 2500 to 1 and greater than 1 to 1.

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