United States Patent

Kirkpatrick

[15] **3,677,329**

[45] **July 18, 1972**

[54] ANNULAR HEAT PIPE

[72] Inventor: **Milton E. Kirkpatrick**, Palos Verdes Peninsula, Calif.

[73] Assignee: **TRW Inc.**, Redondo Beach, Calif.

[22] Filed: **Nov. 16, 1970**

[21] Appl. No.: **89,705**

Related U.S. Application Data

[60] Division of Ser. No. 797,725, Jan. 31, 1969, Continuation-in-part of Ser. No. 637,193, May 9, 1967, abandoned.

[52] **U.S. Cl.** **165/105**, 219/326, 219/399

[51] **Int. Cl.** **F28d 15/00**

[58] **Field of Search** 165/105; 219/325, 326, 399, 219/400, 406

[56] **References Cited**

UNITED STATES PATENTS

2,616,628	11/1952	Guild	165/105 X
3,405,299	10/1968	Hall et al	165/105 X
3,490,718	1/1970	Vary	165/105 X
1,987,119	1/1935	Long	219/325
2,820,134	1/1958	Kobayashi	165/105 X
3,327,772	6/1967	Kodaira	165/105 X
3,229,759	1/1966	Grover	165/105

OTHER PUBLICATIONS

Deverall, J. E. et al., High Thermal Conductances Devices, Los Alamos Scientific Lab., Univ. of Cal., 4/1965, pp. 1, 34, 35.

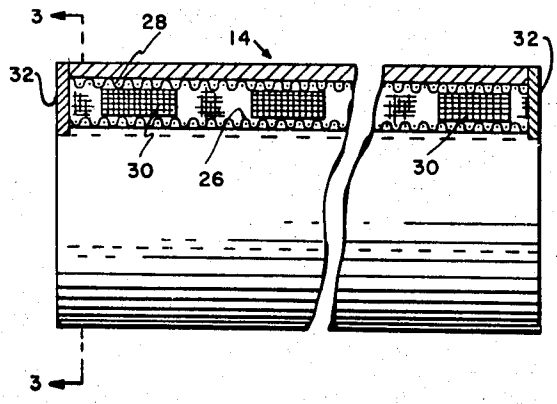
Primary Examiner—Albert W. Davis, Jr.

Attorney—Daniel T. Anderson, Jerry A. Dinardo and Donald R. Nyhagen

[57] **ABSTRACT**

Spaced inner and outer tubes form a closed annular chamber whose inner surfaces contain coverings of wick material that are interconnected through vane-like wicks. The wick material transports a vaporizable working fluid from cold areas where the vapor condenses to warm areas where the fluid vaporizes. An isothermal working space is produced within the central volume bounded by the inner tube and along its entire length, which may be used to advantage for oven or furnace applications or for providing an isothermal jacket.

7 Claims, 9 Drawing Figures



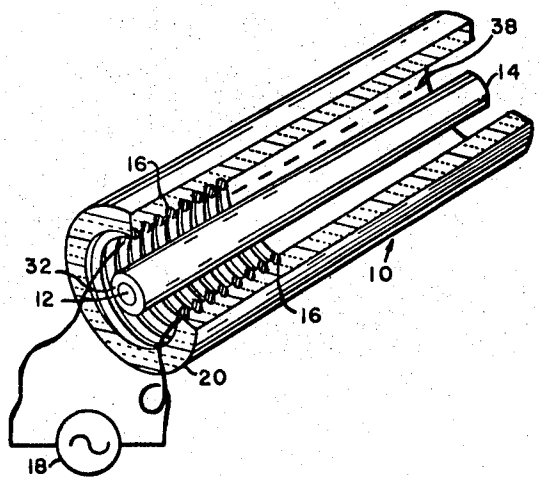


Fig. 1

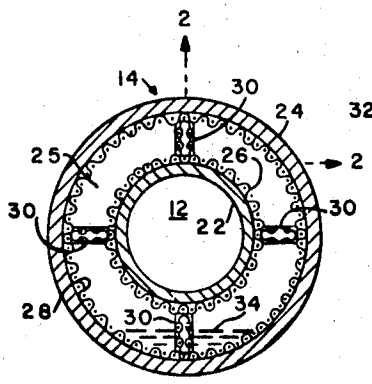


Fig. 3

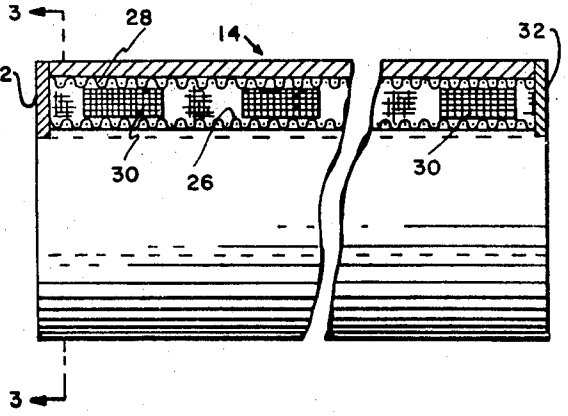


Fig. 2

Milton E. Kirkpatrick
INVENTOR.

BY Jerry G. Dinardo
AGENT

Fig. 4

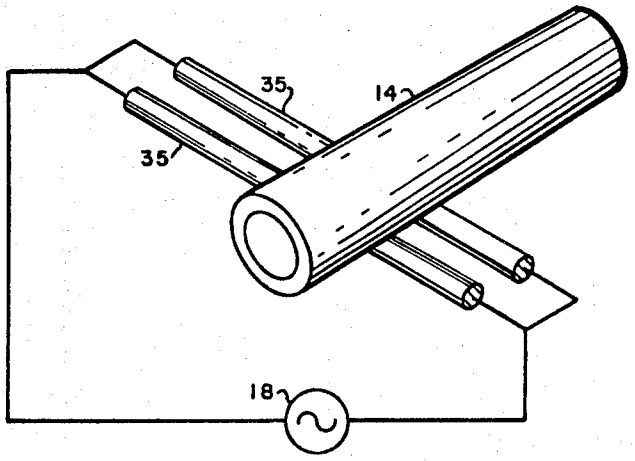
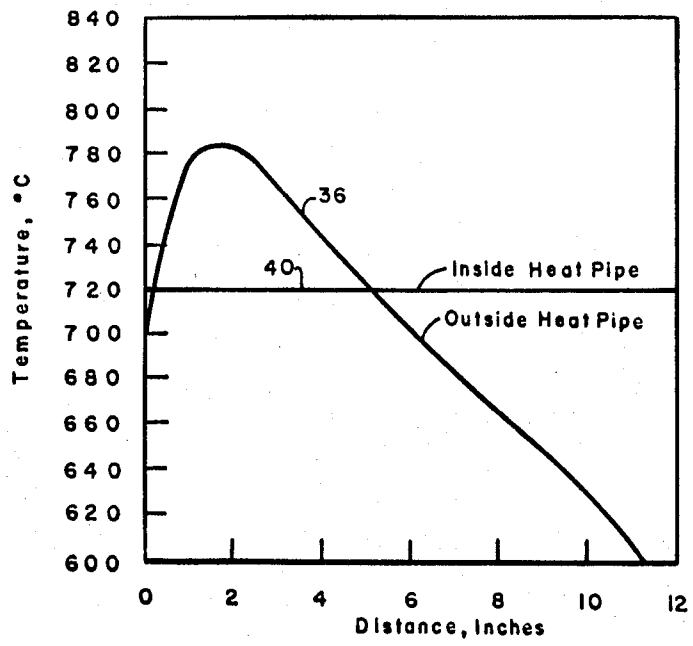


Fig. 5



Milton E. Kirkpatrick
INVENTOR.

BY Jerry A. Diuardo
AGENT

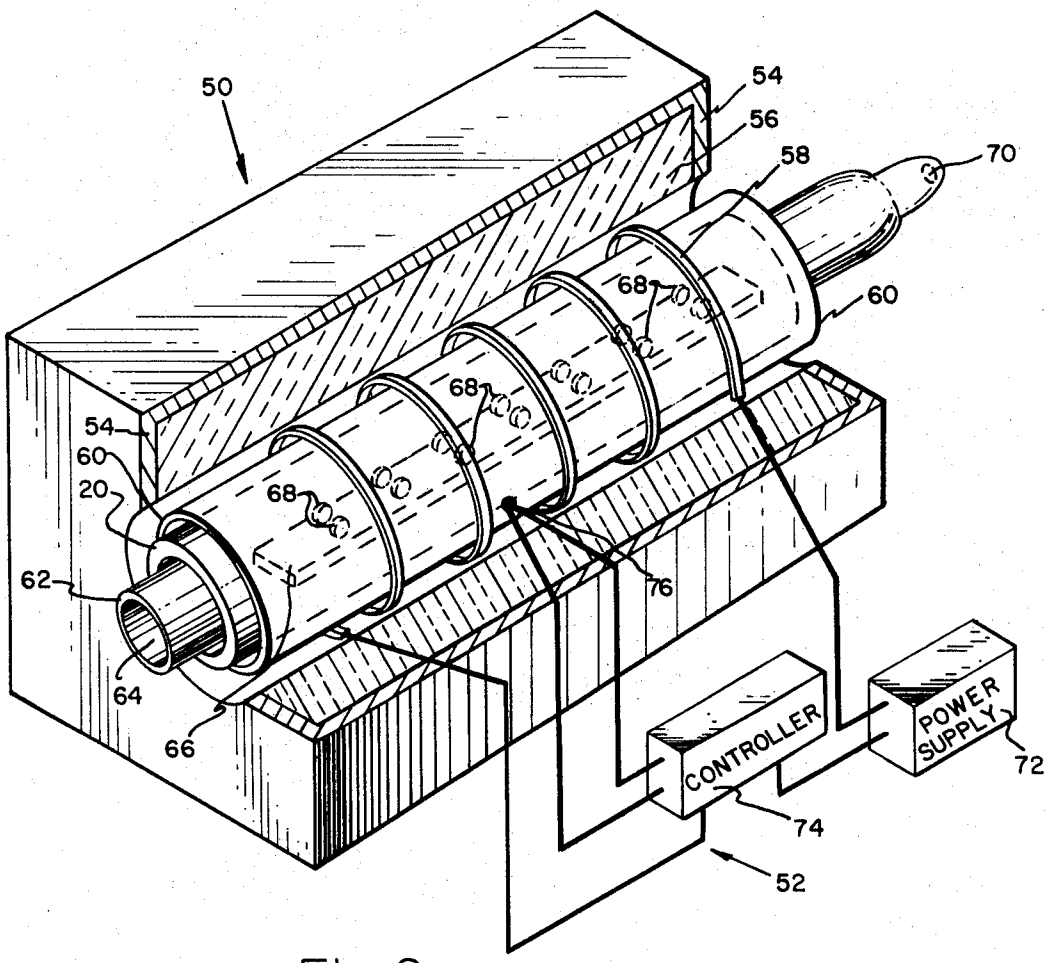


Fig. 6

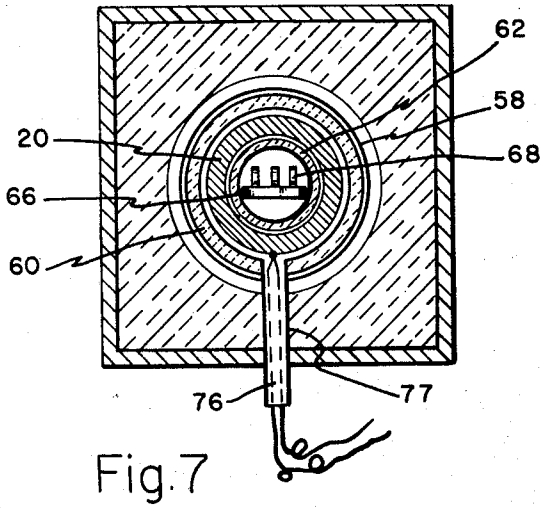


Fig. 7

Milton E. Kirkpatrick
INVENTOR.

BY Jerry G. Dinardo
AGENT

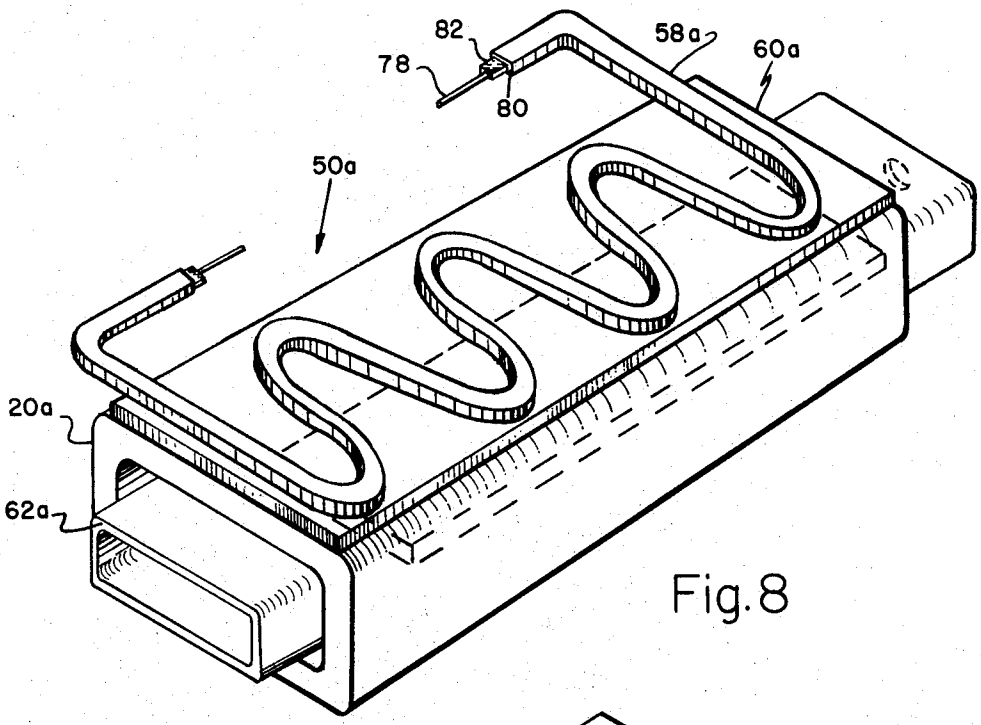


Fig.8

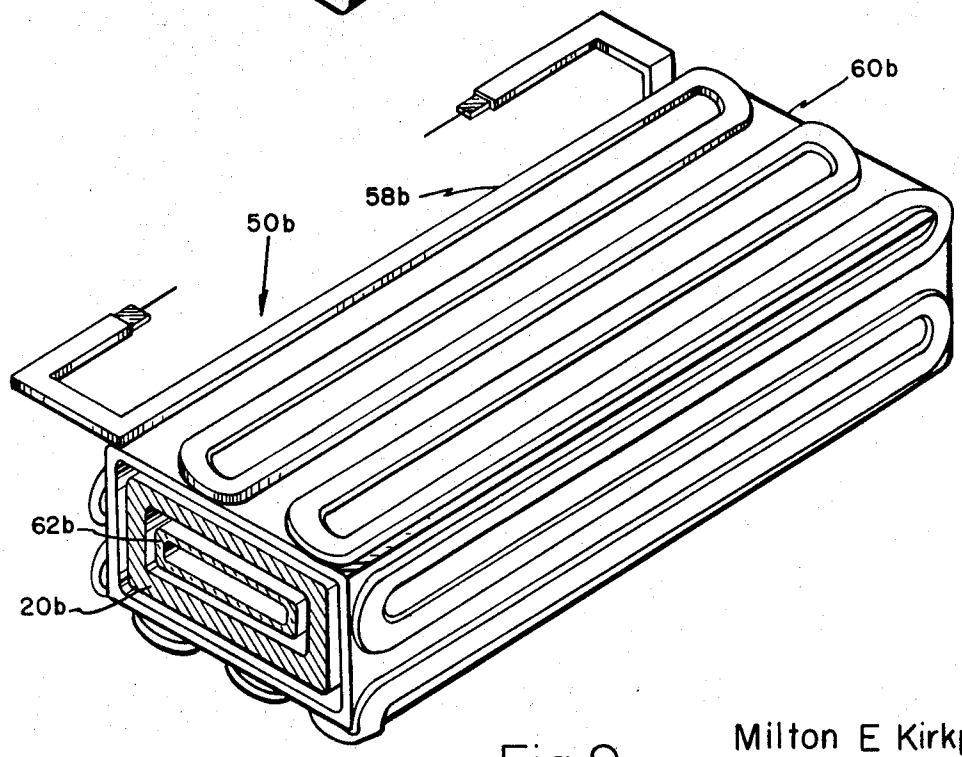


Fig.9

Milton E Kirkpatrick
INVENTOR.

BY Jerry G. Dinardo
AGENT

ANNULAR HEAT PIPE

CROSS-REFERENCE TO RELATED APPLICATION

This application is a division of application Ser. No. 797,725, filed Jan. 31, 1969, which in turn is a continuation-in-part of application Ser. No. 637,193, filed May 9, 1967, now abandoned.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to heat transfer devices, and particularly to devices employing capillary fluid transport, which are of such configuration that lends itself especially to oven or furnace applications.

2. Description of the Prior Art

The concept and art of building reflux boilers is well developed and dates back to papers on the subject during the 1930's. A "heat pipe" works on the principle of a reflux boiler and is extremely efficient in terms of transferring large thermal heat fluxes. Example of "heat pipe" devices are described in U.S. Pat. Nos. 3,152,774 and 3,229,759, issued to T. Wyatt and G. M. Grover, respectively. The basic "heat pipe" is a closed tube which has a layer of porous wick material attached to the interior surface of the tube wall. The tube or pipe is partially filled with a fluid, the specific fluid being determined by the temperature range desired, which wets the porous wick material and spreads throughout the wick material by capillary forces.

When a sufficient heat flux is applied to any point on the surface of the pipe, liquid will be vaporized. Energy equivalent to the heat of vaporization is carried away from the high heat flux region by the vapor that migrates throughout the interior regions of the pipe. The vapor will recondense on any and all interior surfaces which are at temperatures below that of the vaporizing surface, thereby giving up the heat of vaporization to all cooler surfaces.

The recondensed fluid is then transported by capillary forces back to the vaporization region, or high heat flux input zone, to continue the closed loop process of transporting and delivering thermal energy to any and all cool regions of the pipe. As a result of this action, the "heat pipe," although heated only in one small region, quickly becomes an isothermal surface; i.e. all surface temperatures on the pipe are equal or nearly equal no matter what the distribution of heat flux input may be.

Inasmuch as the present invention may advantageously be used to provide a diffusion furnace for the semiconductor industry, a brief description of such diffusion furnaces will be given. In the present state of the art, a diffusion furnace has a long processing tube two to three feet in length and several inches in diameter. The processing tube is surrounded along its length by a long helical heating coil, which is divided into three coil portions, namely a long central portion and two shorter end portions. The three coil portions are separately supplied with electrical heater power so as to produce three separately thermostatically controllable heating zones within the processing tube. The three zones are necessary to achieve a flat temperature profile along the longest possible length of the processing tube. A flat temperature profile is necessary to assure that all the semiconductor wafers, which are placed in a boat within the processing tube, will be subjected to the same thermal diffusion processing conditions. The diffusion process consists of introducing a gaseous impurity or dopant material into the processing tube while the boatload of semiconductor wafers are heated at about 1300° C.

Despite such an elaborate three zone heating arrangement, substantially less than the entire length of the processing tube attains a flat temperature profile. Furthermore, some rather complex electrical control circuitry is required to control or modify the temperatures of the three zones so that the furnace not only attains a flat temperature profile but also maintains it under different boatload conditions.

Reference may be had to the following U.S. Pats. for fuller descriptions of diffusion furnaces and the problems associated therewith:

3,291,969 B. J. Speransky et al Dec. 13, 1966
3,299,196 C. A. Lasch, Jr., et al Jan. 17, 1967
3,311,694 C. A. Lasch, Jr. March 28, 1967
3,370,120 C. A. Lasch, Jr. Feb. 20, 1968
3,385,921 G. P. Hampton May 28, 1968
3,387,078 W. S. Montgomery, Jr., et al June 4, 1968
3,396,955 R. G. Martinek Aug. 13, 1968

SUMMARY OF THE INVENTION

The present invention resides in a uniquely configured structure utilizing the basic "heat pipe" concept, and in the recognition that such structures advantageously can be used and ought to be used in certain types of furnaces, such as diffusion furnaces. Interior surfaces of an annular pipe are provided with a porous wick material, such as sintered metals, wire screens, or other porous compacts, to provide complete interconnection of fluid flow paths. When charged with a working fluid which wets the wick material and has a suitable vapor pressure matching the desired temperature range of interest, the isothermal annular "heat pipe" may be used for a variety of heat transfer applications. In particular, when employed in a diffusion furnace, it will produce a flat temperature profile along the entire length of the processing tube or chamber by the use of a single electrical heater coil and a single temperature controller.

BRIEF DESCRIPTION OF THE DRAWING

In the drawing:

FIG. 1 is a partially broken away diagrammatic view in perspective of a tube furnace employing a structure in accordance with the invention;

FIG. 2 is a side view, partly in section, of the structure;

FIG. 3 is a sectional view taken along line 3—3 of FIG. 2;

FIG. 4 is a diagrammatic view showing an alternative form of heater for the structure of FIG. 2;

FIG. 5 is a graph of curves showing the temperature, as a function of distance along the furnace of two different regions thereof;

FIG. 6 is a perspective view, with portions removed, of a diffusion furnace employing an annular heat pipe according to the invention;

FIG. 7 is a cross-sectional view of the furnace assembly of FIG. 6; and

FIGS. 8 and 9 are perspective views of alternative forms of diffusion furnaces employing annular heat pipes of rectangular cross-section.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1, there is shown an oven or furnace **10** provided with a central isothermal working space **12** formed within an annular "heat pipe" **14**. An electrical heater coil **16** is wound around one end of the "heat pipe" **14** and receives electrical power from a voltage source **18**. The heater coil **16** may be embedded in a thermal insulation sheath **20** that surrounds the "heat pipe" **14** along its length. The insulation sheath **20** serves to minimize heat loss from the "heat pipe" **14** to the surrounding atmosphere.

As shown more clearly in FIGS. **2** and **3**, the "heat pipe" **14** includes concentric inner and outer cylindrical metal tubes **22** and **24** respectively. The space between the tubes **22** and **24** forms an annular chamber **25**. The surfaces of the tubes **22** and **24** disposed within the annular chamber **25** are covered with linings **26** and **28** of porous wick material. The two wick linings **26** and **28** are spaced apart and joined together by short spacer elements **30** of wick material that are spaced along the length of the tubes **22** and **24**.

The annular chamber **25** is closed at both ends by cover plates **32**, such as the one shown in FIG. **1**, which leave the isothermal working space **12** open for easy access from the

outside. The annular chamber **25** is evacuated of non-condensable gases, such as air, and contains a vaporizable fluid **34** of sufficient quantity to wet the entire wick material by capillary action. The specific fluid depends upon the operating temperature desired for the "heat pipe" **14**.

The wick material for the linings **26** and **28** and spacer elements **30** may be in the form of sintered metal, wire screens, or other porous compacts having voids or openings of capillary size and capable of transporting the vaporizable fluid **34**.

In the operation of the furnace **10**, the heater coil **16** is energized to heat the portion of the annular "heat pipe" **14** surrounded thereby. The fluid **34** heated thereby vaporizes and the vapor carries away from the high heat flux region thermal energy equivalent to the heat of vaporization. The vapor migrates through the annular chamber **25** where it condenses on all interior surfaces that are below the temperature of the vaporizing surface, thereby giving up the heat of vaporization to and raising the temperature of all the cooler surfaces. Continuous vapor flow paths are provided along the annular extent of the annular chamber **25** by means of the linear spacing between the spacer elements **30**. The condensed fluid **34** is then transported by capillary action through the wick material from these condensing regions to the vaporizing region or high heat flux input zone, where the fluid **34** again vaporizes.

By means of this closed loop process, thermal energy supplied by the heater coil **16** is transported and delivered to any and all cooler interior regions of the chamber **25**. The result is that the entire surface of the "heat pipe" **14** quickly becomes an isothermal surface when operating in the temperature range specified by the working fluid, and the volume within the isothermal working space **12** of the furnace **10** is uniform in temperature along the entire length of the "heat pipe" **14**.

For a specific working fluid, there is a range of equilibrium temperatures over which the device of this invention will provide isothermal conditions. The lower limit of the equilibrium temperature range is determined by the thermodynamic properties of the working fluid, namely the vapor pressure and the heat of vaporization. The upper limit of the equilibrium temperature range is determined by the mechanical ability of the device to withstand the positive pressures of the vapor relative to the surrounding atmosphere.

The working space **12**, being devoid of fluid **34**, can be used as an oven to process various articles of manufacture, such as semiconductive devices, without danger of contamination by the working fluid **34**. In addition, the furnace **10** may be used to provide an isothermal environment for various components requiring uniform thermal distribution, with the oven shaped in conformity therewith. Accordingly, whereas the furnace **10** has been shown as having a circular, cylindrical shape, it may have a rectangular cross-section or even a complex cross-sectional shape.

In accordance with an exemplary operative embodiment, the tubes **22** and **24** consisted of stainless steel cylinders having lengths of 12 inches, inside diameters of 1.5 inches and 1.9 inches respectively and outside diameters of 1.6 inches and 2.0 inches respectively. The wick material was fabricated from four multiple layers of 100 mesh stainless steel screen. The vaporizable fluid was potassium metal.

For applications where temperatures in excess of 1000° C are required, such as in the treatment of semiconductor devices, working fluids such as lithium or other liquid metals having the desired vaporization temperature can be employed. For applications requiring high operating temperatures it will prove advantageous to utilize silicon carbide rods as heating elements, rather than heater coils. In FIG. **4**, for example, two or more such rods **35** may be arranged side by side beneath the annular "heat pipe" **14** as shown. The rods **35** may be connected in parallel with the voltage source **18**.

FIG. **5** shows curves of temperatures taken along the length of the furnace **10** at two different regions thereof. Curve **36** refers to the region indicated in FIG. **1** by dashed line **38** as occupying the space adjacent to the inside surface of the insulation sheath **20**. Curve **40** refers to the region on the interior surface of the inner tube **22**; that is, the surface that bounds the central working space **12**. Temperature is plotted along the ordinate and distance along the furnace **10** is plotted along the abscissa. It is seen that the temperature external of the annular "heat pipe" **14** increases from 700° C on one end adjacent to the heater coil **16** to a maximum of over 780° C just 2 inches away, and then drops to below 600° C at the opposite end. In contrast, the temperature on the interior surface of the inner tube **22** is uniformly at 720° C along the entire length.

The present invention provides special advantages when used for processing semiconductor devices. For example, in the art of semiconductor device manufacture, it is necessary to heat wafers of silicon in the presence of dopant materials in a furnace or oven at temperatures of the order of 1000° C. With furnaces in present use, the temperature is fairly uniform in the central portion but drops substantially at the ends. As a result, about 60 percent of the furnace length is unusable. With the present invention, substantially the entire length of the furnace is uniform in temperature, and a much greater length of the furnace zone may be used for treating semiconductor devices. Consequently, in a particular application, the equivalent power consumption for the processing can be significantly reduced.

Furnaces presently in use utilize several electrical heaters distributed along the furnace length, and each of the heater coils may be individually thermostatically controlled. Maintenance problems arise from the fact that failure can occur from one of the number of heating coils and control circuits. Maintenance problems as well as systems costs are reduced in the present invention in that only a single heater source and control circuit are required.

The present invention provides additional special advantages when used for elevated temperature mechanical property testing. In the art of property testing, a furnace is employed to heat the subject specimen. Furnaces in present use in the art, employ a multiplicity of heater coils along the length of the furnace which are individually controlled and adjusted to provide semi-uniform temperature over the active region. When adjusted, such a furnace will provide temperature uniformity of several degrees variance over the length of interest. During the test sequence, any change in heat balance due to changing test conditions will effect and degrade the thermal uniformity within the furnace volume. The present invention eliminates the need for any manual or semiautomatic adjustment of the position of thermal input or temperature uniformity within the volume of the isothermal working space. A single automatic temperature control is thus all that is required to maintain uniformity, throughout the working volume, over any desired temperature within the working range of the heat transfer fluid.

The invention will now be described as applied to the construction of a diffusion furnace for processing semiconductors. Referring to FIGS. **6** and **7**, there is shown a diffusion furnace consisting of a furnace assembly **50** and a power control system **52**. The furnace assembly **50** includes an outer cabinet or casing **54** lined with thermal insulation **56**. Extending longitudinally and centrally of the casing **54** and supported by the insulation **56** is a helical heating coil **58** that is wound around a cylindrical ceramic support tube **60**.

The heating coil **58** serves the same function as the heater coil **16** of FIG. **1**, namely that of supplying heating energy to the annular heat pipe **20**, which in this diffusion furnace is supported within the support tube **60**. To this end, the heating coil **58** may be formed of high resistance wire that will heat to a high temperature when supplied with electrical current of 60 cycle frequency. Alternatively, the heating coil **58** may comprise metal tubing of high electrical conductivity which, when furnished with radio frequency current, will cause the annular heat pipe **20** to heat up by electromagnetic induction.

A cylindrical processing tube **62** made of suitable material such as quartz is supported within the annular heat pipe **20** and extends longitudinally through both ends thereof. The processing tube **62** is provided with an open end **64** through

which may be inserted a boat **66** containing wafers **68** of silicon or other semiconductor. The other end of the processing tube **62** is provided with a smaller opening **70** through which a suitable gaseous dopant material may be introduced into the processing tube for diffusion into the semiconductor wafers **68**.

It will be observed that the wafer-loaded boat **66**, or a plurality thereof arranged end to end, may extend substantially the entire length of the annular heat pipe **20** and even beyond the extremities of the heating coil **58**. The reason for this is that the effective heating zone for heating the semiconductor wafers **68** is determined by the interior of the annular heat pipe **20** rather than the heating coil **58**. The effective heating zone has a flat temperature profile along the entire length of the annular heat pipe **20**.

The power control system **52** includes a power supply **72** for furnishing electrical energy to the heating coil **58**. The power supply **72** is connected to the heating coil **58** through a controller **74**. A thermocouple **76** contacting the annular heat pipe **20** is connected to the controller **74**. The thermocouple **76**, which may be supported in a tube **77**, as shown in FIG. **7**, senses changes in heat pipe temperature above and below a given set point for which circuits in the controller **74** are set. The circuits in the controller **74** operate to turn on power to the heating coil **58** when the temperature falls below the set point and to turn off power to the heating coil **58** when the temperature rises above the set point.

Temperature control systems for diffusion furnaces are well known in the art and therefore the controller **74** requires no further detailed description. It will suffice to say that the controller **74** may be one of the kind disclosed in U. S. Pat. No. 3,291,969 issued Dec. 13, 1966, to B. J. Speransky et al, for controlling the central zone B of the heating coil **11** of that patent.

The power supply **72** may be designed to furnish **60** cycle alternating current to the heating coil **58** if the latter operates on the principle of resistance heating. On the other hand, if the heating coil **58** is an electromagnetic induction heating coil, the power supply **72** may be designed to furnish radio frequency current to the heating coil **58**.

It will be seen that the diffusion furnace thus described is much simpler in the construction of its furnace assembly **50** and its control system **52** than the corresponding structure of conventional diffusion furnaces. The inclusion of an annular heat pipe according to the invention permits the use of a single heater coil instead of three and a single temperature control system instead of three. The annular heat pipe **20** provides a flat temperature profile along its entire interior length, thereby increasing the capacity of the semiconductor processing zone. Furthermore, whenever it is desired to change the temperature of the furnace, the temperature will rise or fall uniformly along the entire length of the heating zone.

Referring now to FIG. **8**, there is shown a modified form of diffusion furnace assembly **50*a*** which has a rectangular cross-section. Thus, the processing tube **62*a*** and annular heat pipe **20*a*** are rectangular instead of circular. A heater element **58*a*** of flat sinuous form is mounted adjacent to a surface of the heat pipe **20*a***, such as the top surface thereof. The windings of the heater element **58*a*** extend at an angle to the longitudinal axis of the heat pipe **20*a*** and processing tube **62*a***. With this flat configuration, it is preferable that the heater element **58*a*** be of the resistance wire heating type. The heater element **58*a*** may be designed for direct thermal contact with the annular heat pipe **20*a***. For example, the heater element **58*a*** may comprise a central current carrying conductor **78** spaced from an outer metal sheath **80** by electrical insulation **82**. Alternatively, for convenience in assembly or disassembly, the heater element **58*a*** may be mounted on a flat support member **60*a***, which itself is mounted on the heat pipe **20*a***. For ease in illustration, the remaining parts of the furnace assembly **50*a*** are not shown, it being understood that it contains similar parts corresponding to the insulation **56** and casing **54** of FIGS. **6** and **7**. Likewise, a control system **52** similar to that already described in connection with FIGS. **6** and **7** may be used with the rectangular furnace assembly **50*a***.

An additional advantage of incorporating an annular heat pipe in a diffusion furnace is apparent in FIG. **8**. That is, the heating element **58*a*** need not envelope the processing tube **62*a***, as is required in conventional diffusion furnaces. It is sufficient to apply all the required thermal input energy to a localized area of the heat pipe **20*a***, such as the top surface or a portion thereof, and through the operation of the heat pipe **20*a***, the entire surface area thereof will attain an isothermal condition. Furthermore, it is not necessary, in the design of the heater element **58*a***, that great regard be given to precise spacing between turns or windings, or in uniformity in the lengths of the windings.

FIG. **9** shows another form of rectangular diffusion furnace **50*b*** that is similar to that of FIG. **8**. In this embodiment, the heater element **58*b*** has sinuous windings that extend parallel to the longitudinal axis of the heat pipe **20*b*** and process tube **62*b***. The heater element **58*b***, which may be mounted on a support tube **60*b***, may cover all four sides of the heat pipe **20*b*** both longitudinally and circumferentially, as shown, or it may cover a less number of sides or only portions thereof.

A principal advantage of a rectangular configuration for the diffusion furnace assembly is that it minimizes the cross sectional area of the processing tube required for any boat and semiconductor load configuration. This minimizes the heat loss from the open ends of the furnace and improves the temperature profile thereof.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. In combination:

a tubular member having spaced inner and outer walls and interconnecting end walls defining a closed, evacuated annular chamber surrounding a central opening;

means forming a capillary structure on the inner surface of said outer wall and a capillary structure on the outer surface of said inner wall;

additional capillary means interconnecting said capillary structures and including a plurality of groups of wick elements spacing said capillary structures, said wick elements being circumferentially and longitudinally spaced within said annular chamber to provide continuous fluid flow paths through said chamber;

and said annular chamber being evacuated of all non-condensable gases and being partially filled with a substance which is vaporizable from a liquid phase and is capable of transport through said capillary structures and additional capillary means.

2. A heat pipe comprising:

a tubular member having spaced inner and outer walls and intersecting end walls forming a closed, evacuated chamber including an annular space between said spaced walls;

a capillary structure on the inner surface of said outer wall and a capillary structure on the outer surface of said inner wall;

additional capillary means interconnecting said capillary structures and including a plurality of groups of wick elements spacing said capillary structures, said wick elements being circumferentially and longitudinally spaced within said annular space to provide continuous fluid flows paths within said chamber; and

a working fluid partially filling said chamber and formed of a substance that is vaporizable from a liquid phase and is capable of transport through said capillary structures and said additional capillary means.

3. A heat pipe comprising:

a pair of radially spaced inner and outer walls extending longitudinally and circumferentially and closed by end walls to form a hermetically sealed chamber including an annular space between said radially spaced walls;

a capillary structure on the inner surface of said outer wall and on the outer surface of said inner wall;

additional capillary means interconnecting said capillary structures and including a plurality of wick elements extending longitudinally and radially and spaced longitudinally within said annular space to provide continuous fluid flow paths within said chamber; and

a working fluid within said chamber that is vaporizable from the liquid phase and capable of transport through said capillary structures and additional capillary means.

4. The invention according to claim 3, wherein said walls comprise a pair of tubular members substantially equal and coextensive in length;

said end walls joining the adjacent ends of said tubular members to form an elongated annular chamber surrounding an open passageway.

5. The invention according to claim 4, wherein said tubular members are circularly cylindrical.

6. The invention according to claim 3, wherein said capillary structures and said wick elements are formed of metal mesh.

7. The invention according to claim 3, wherein said working fluid is a material selected from the group consisting of potassium and lithium.

* * * * *