US 20050144968A1

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2005/0144968 A1**

Shakespeare (43) **Pub. Date: Jul. 7, 2005**

(54) MEMS BASED MICRO VAPOR COMPRESSION REFRIGERATION SYSTEM FOR MICROELECTRONIC AND PHOTONIC THERMAL CONTROL

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(21) Appl. No.: **11/023,822**

(22) Filed: **Dec. 28, 2004**

Related U.S. Application Data

(60) Provisional application No. 60/533,572, filed on Jan. 2, 2004.

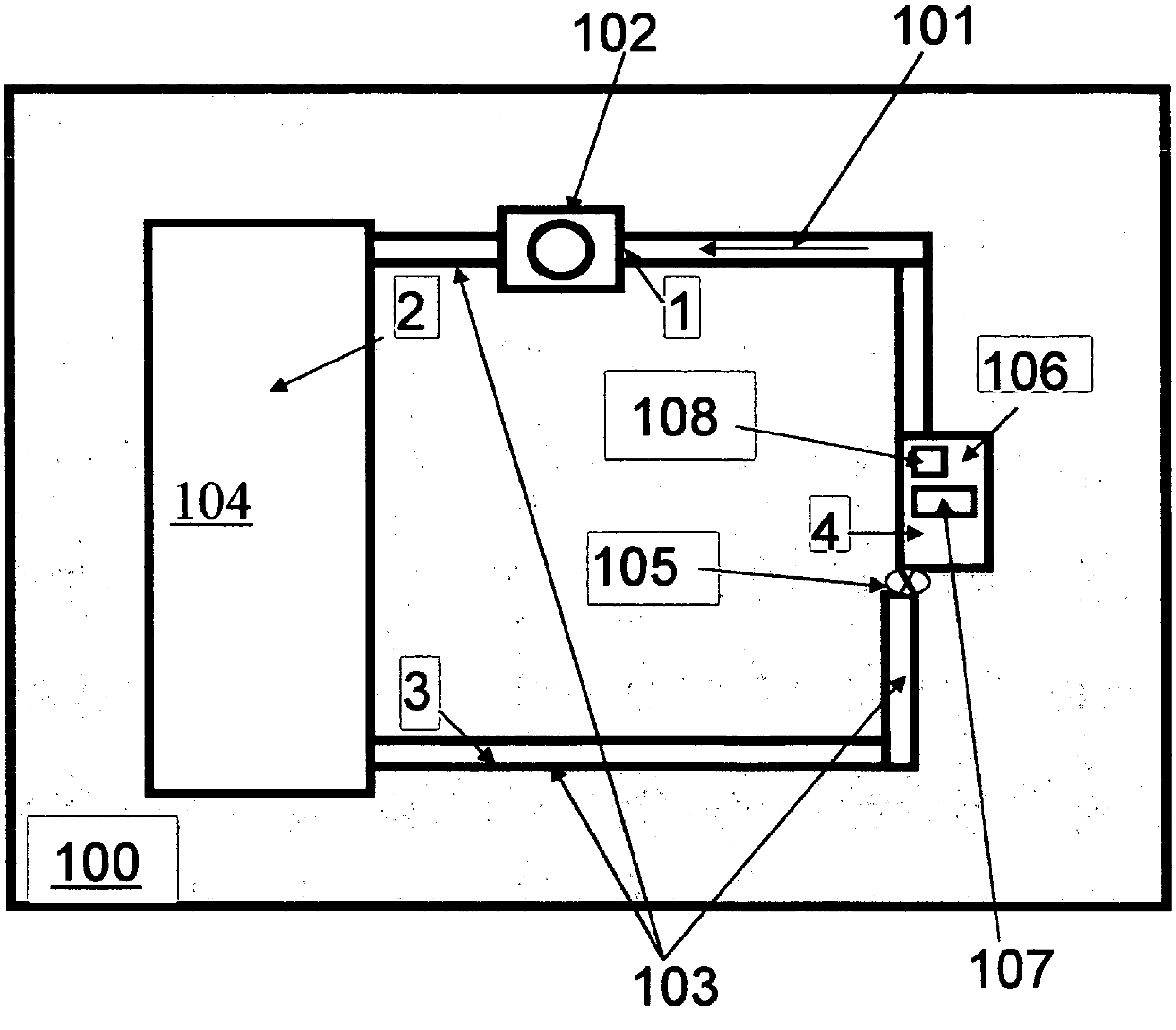
Publication Classification

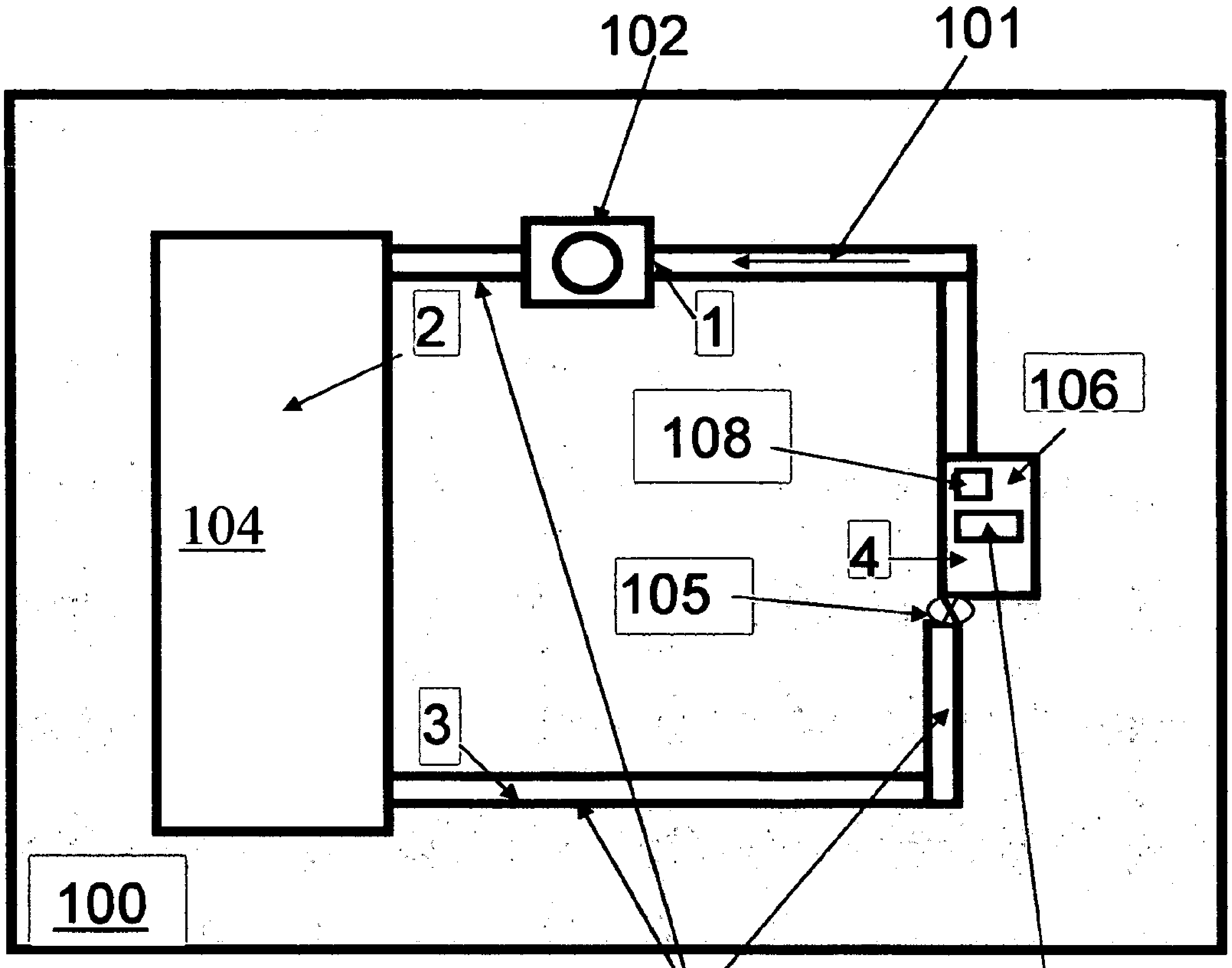
(51) Int. Cl.^{7} **F25D 17/06**; F25D 23/12; F25D 19/00; F25B 1/00

(52) U.S. Cl. **62/298**; 62/498; 62/259.2

(57) ABSTRACT

A micro-refrigerator is fabricated using Micro-Electro Mechanical Systems processing and is used to thermally control photonic or microelectronic circuits. Temperatures below local ambient are possible due to the refrigeration capability of the device and unwanted parasitic heat such as from the walls or lid of an enclosure is minimized due to the small size of the cooled mounting area for the integrated circuit. Localized cooling is provided by jets of vapor droplet mixture controlled to impinge directly onto the hottest regions of a microelectronic or photonic integrated circuit allowing greater circuit density and thermal dissipation at isolated regions within the integrated circuit and advantageously improving performance. Methods of manufacturing micro-scale refrigerator elements including the compressor, evaporator and condenser are defined. This device is a direct improvement over the commonly used thermoelectric cooler for thermal control of microelectronic or photonic devices.




102
101
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2
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Fig. 1

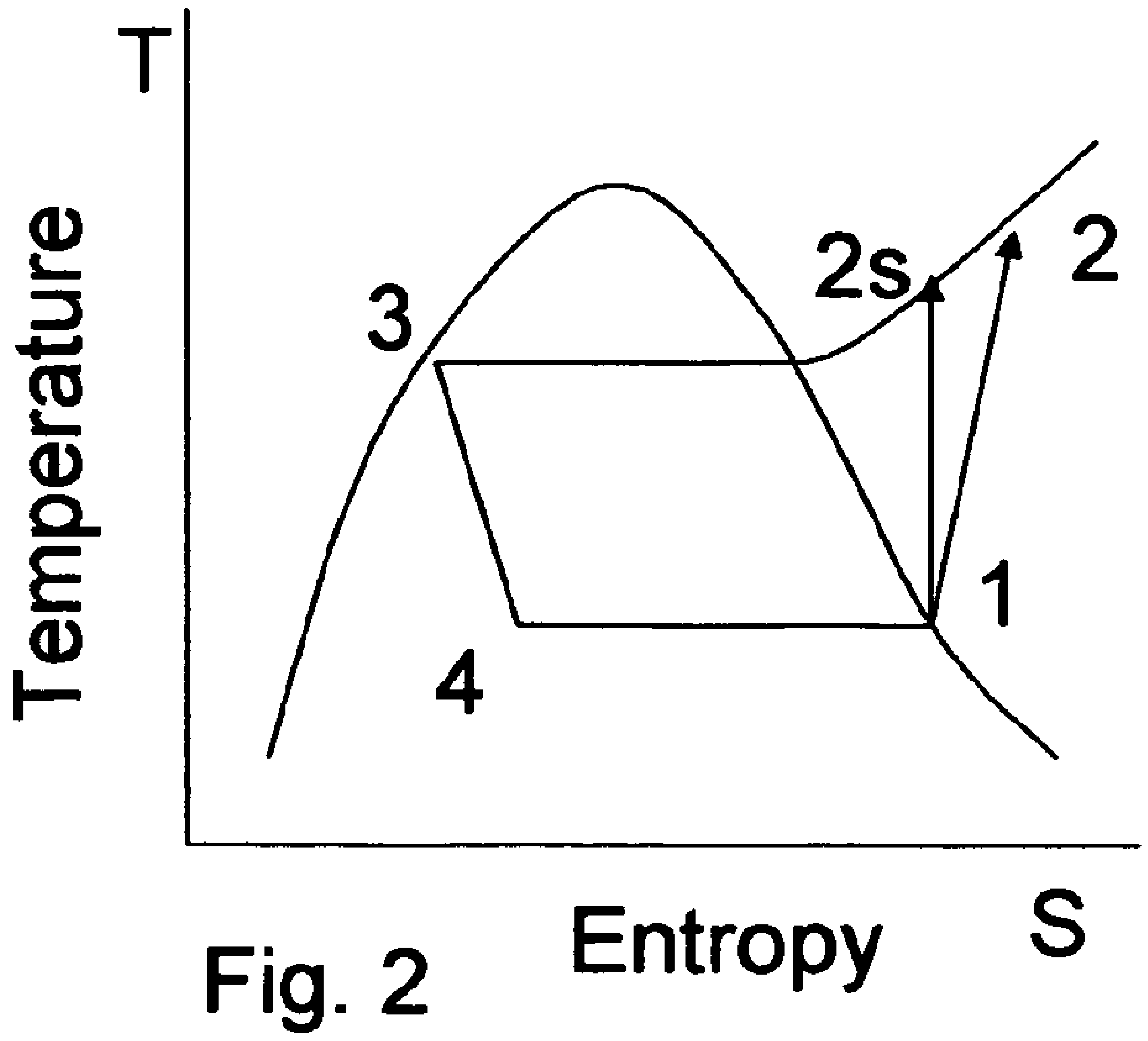
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Fig. 2

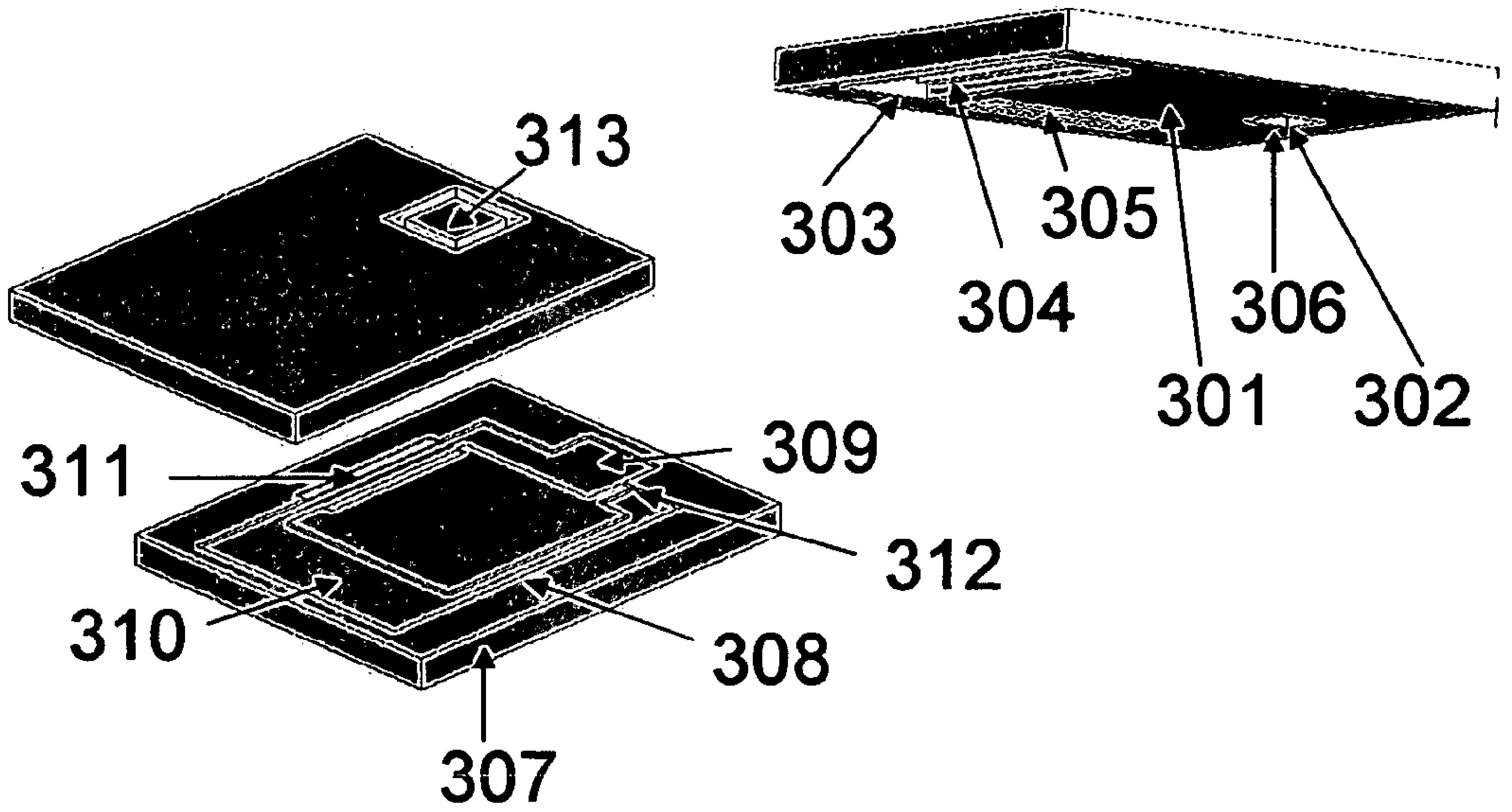


Fig. 3

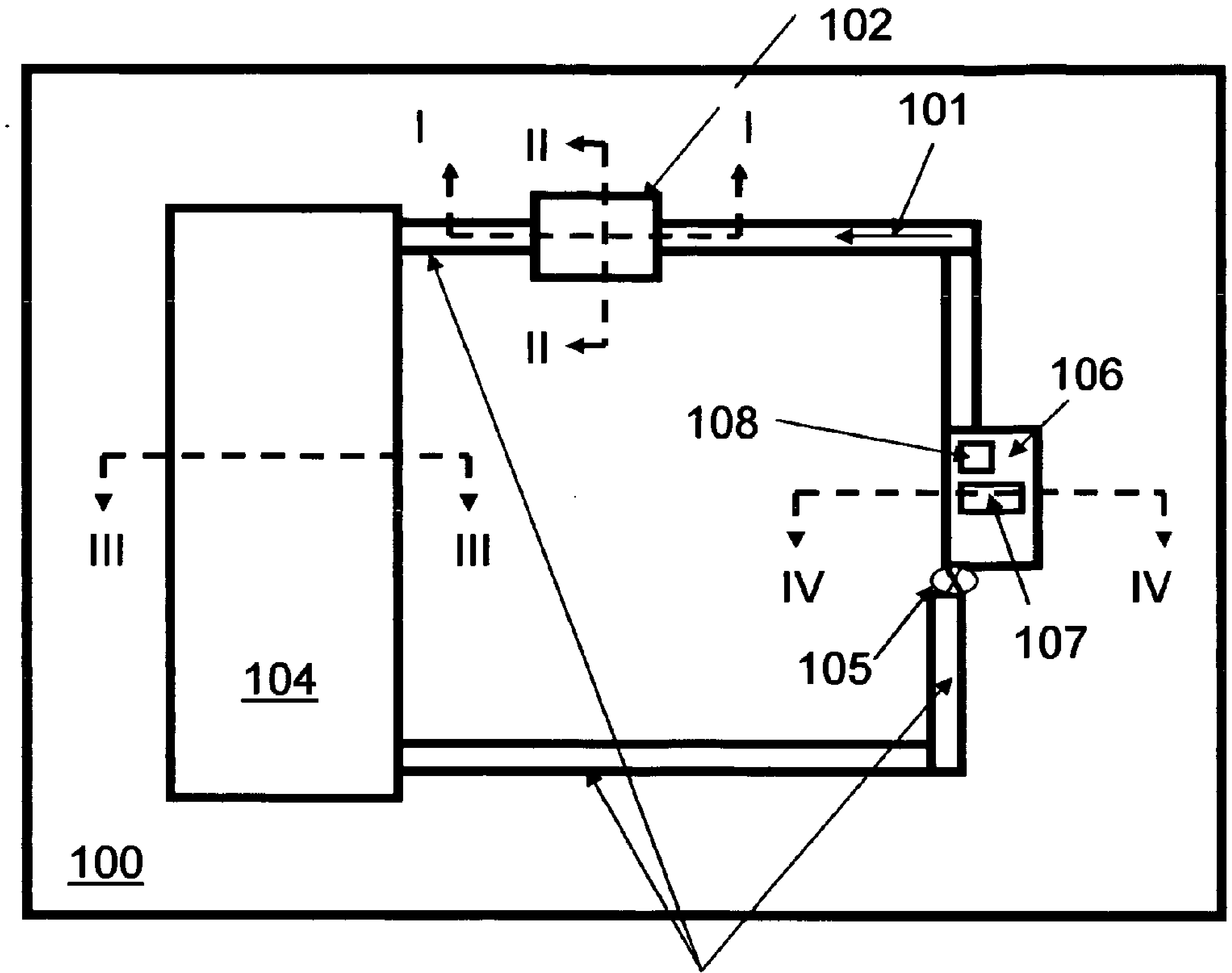
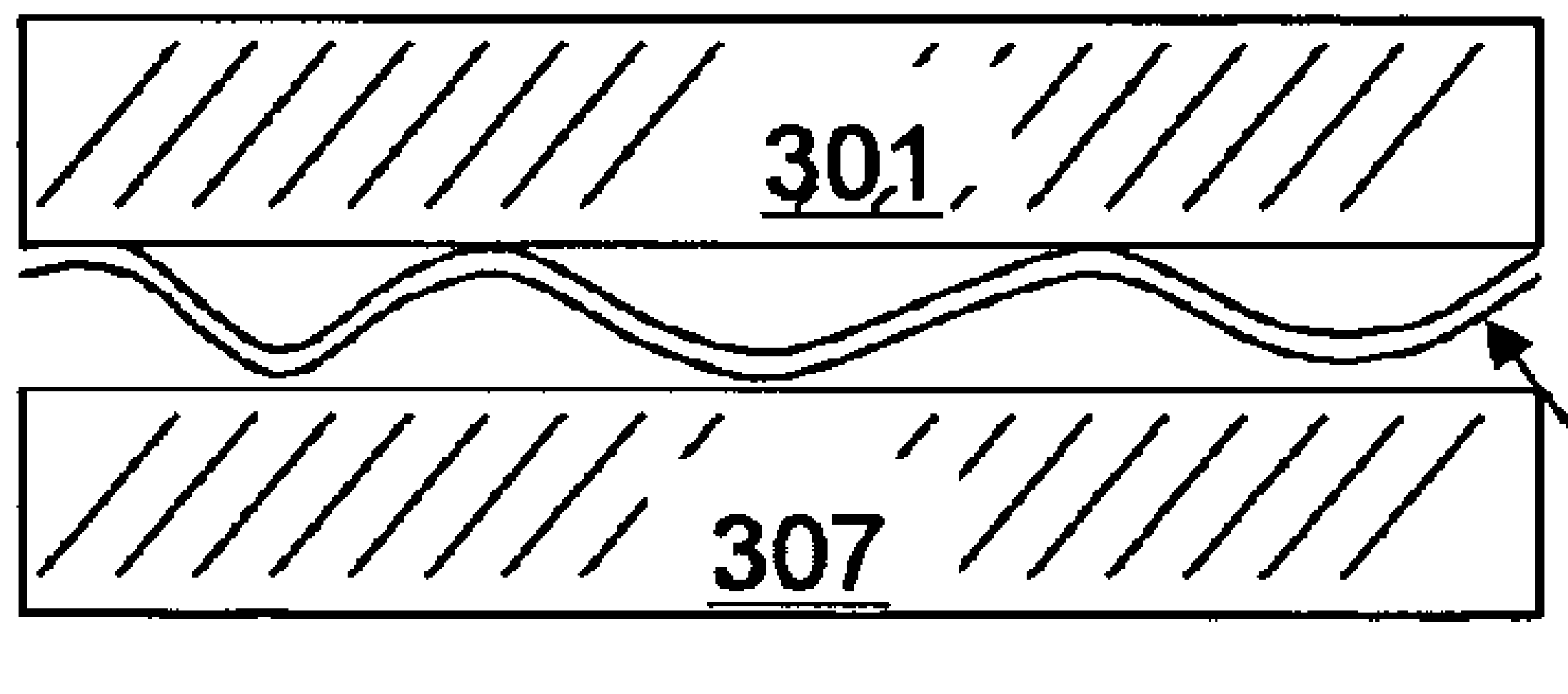
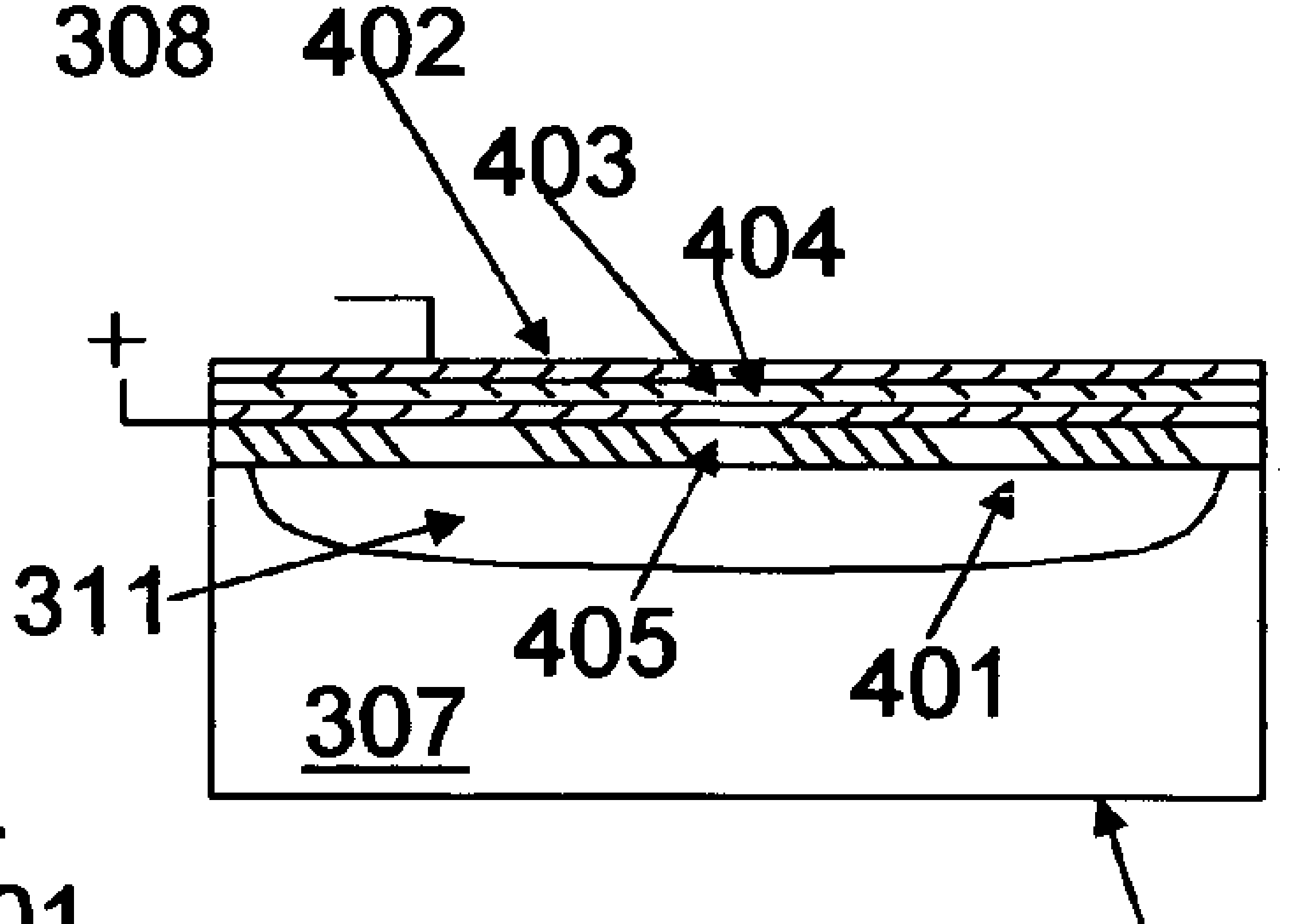


Fig. 4



Section I



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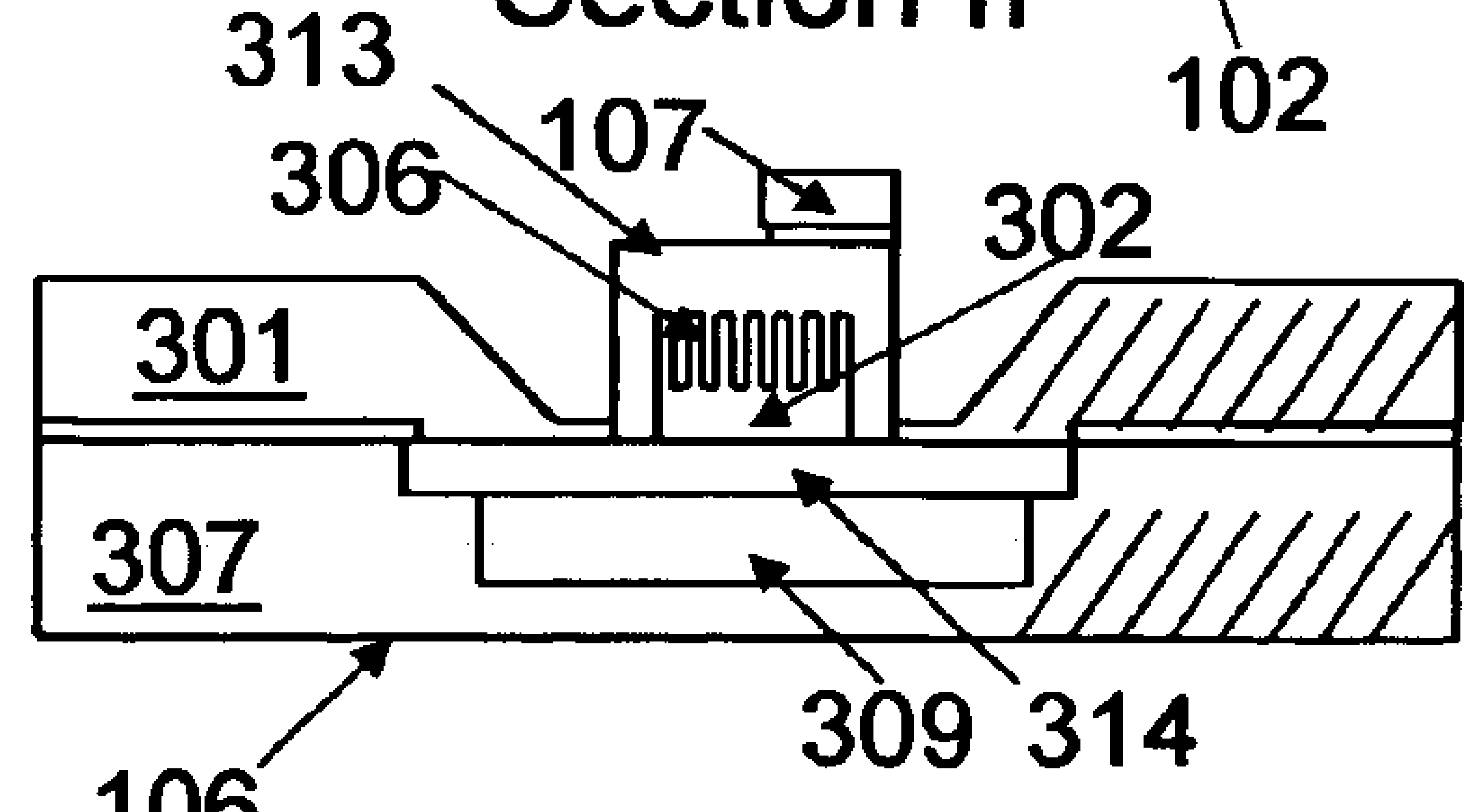
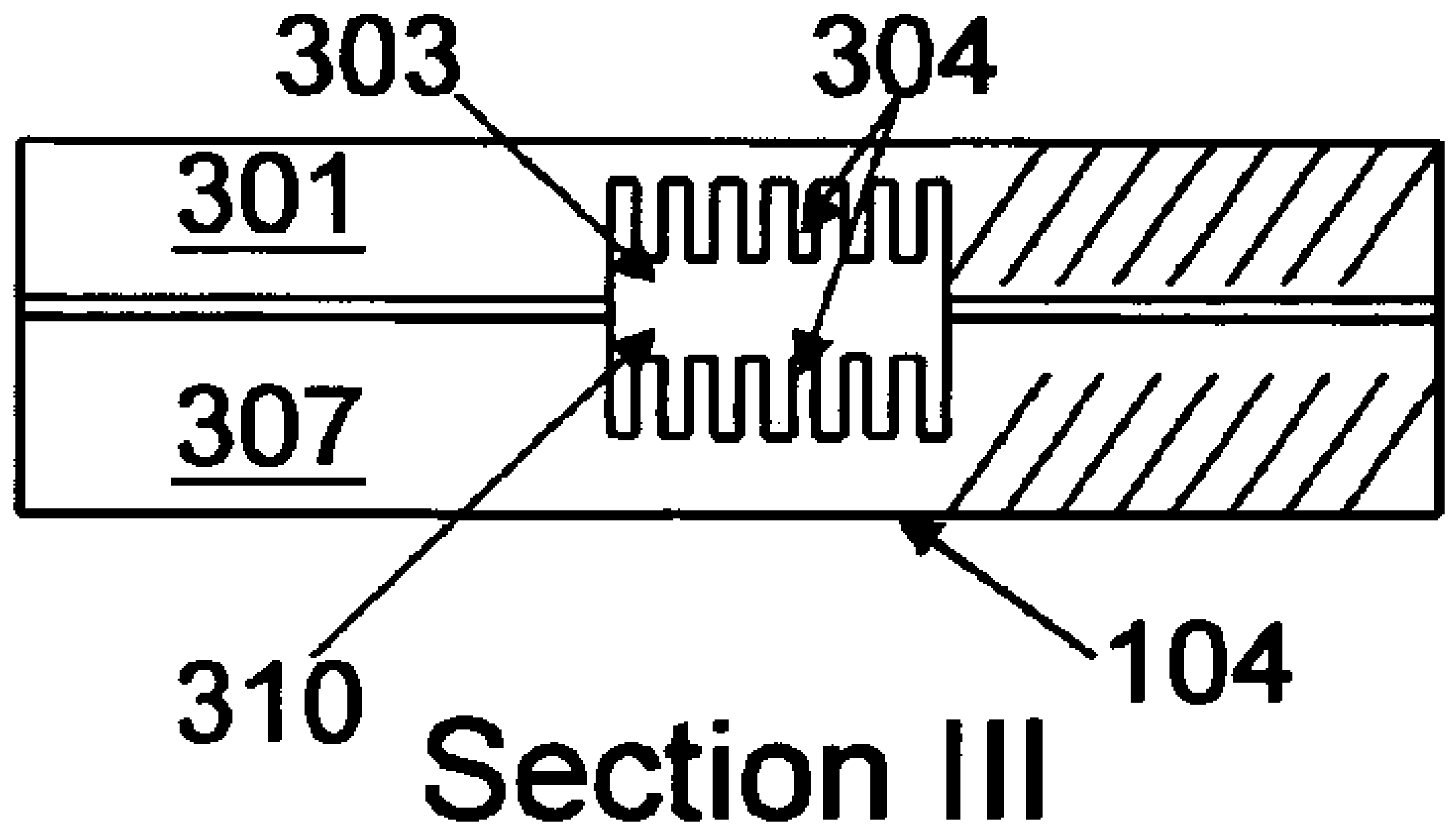


Section IV



Section III

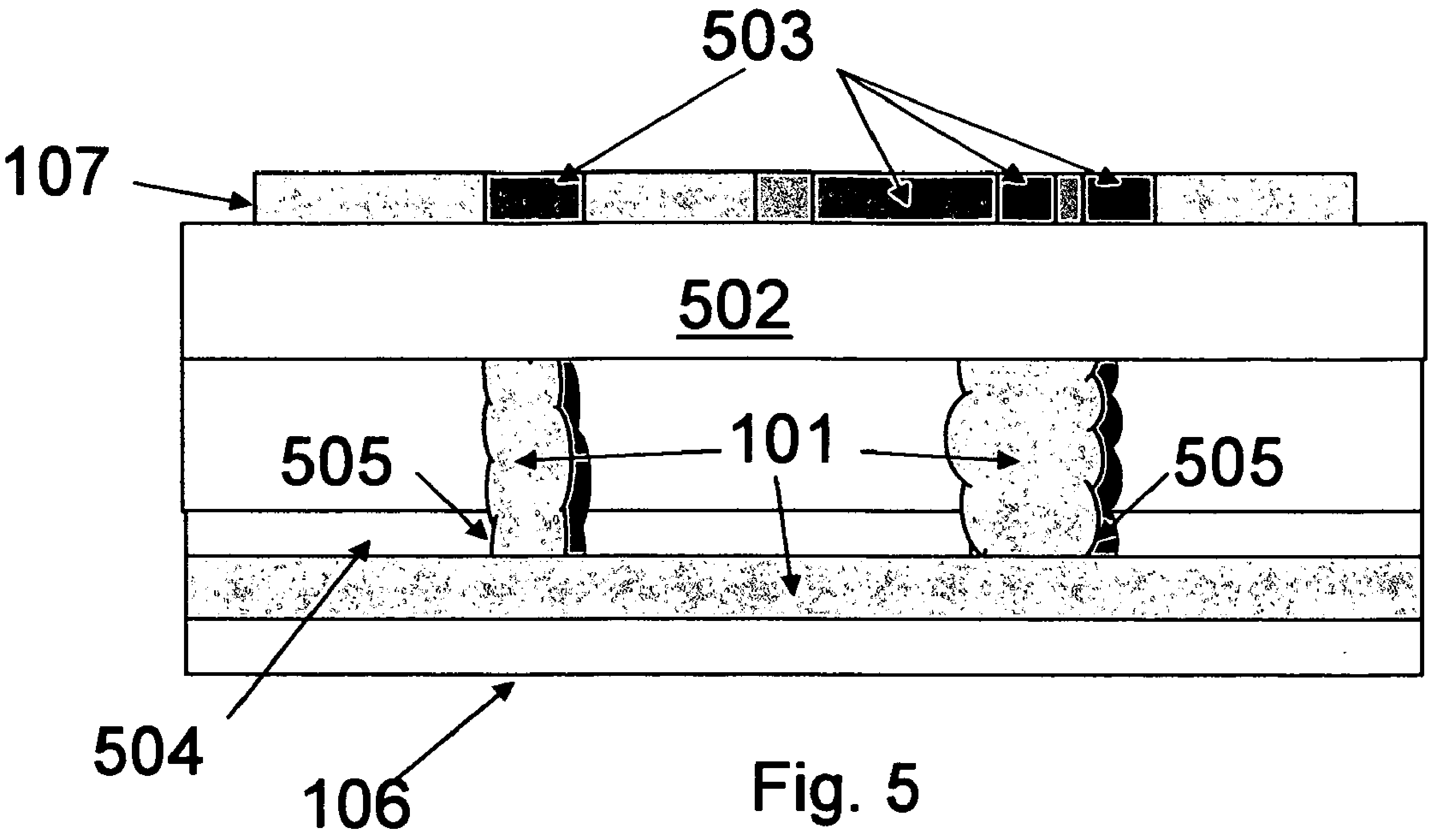


Fig. 5

MEMS BASED MICRO VAPOR COMPRESSION REFRIGERATION SYSTEM FOR MICROELECTRONIC AND PHOTONIC THERMAL CONTROL

FIELD OF THE INVENTION

[0001] The invention pertains to the application of a Micro-Electro Mechanical Systems (MEMS) based micro vapor compression refrigeration system to thermally control electronic or photonic devices for improved performance and lower cost.

BACKGROUND OF THE INVENTION

[0002] Recent advances in fiber optics and photonics have resulted in a vast increase in the volume of information that can be transmitted optically. This has occurred in two fundamental ways. The speed of modulation of the optical signal has increased to upwards of 40 Gb/s and the wavelength spacing between adjacent channels is only a few tenths of a nanometer. To maintain this performance, the temperature of the photonic device must be held to within less than one degree Celsius of the design temperature[1]. This temperature is usually less than the ambient temperature surrounding the device requiring active refrigeration. The technology available for refrigerating the device is limited to either a thermoelectric cooler which utilizes the Peltier effect, or some type of large external refrigeration system with coolant piped to the component. Commercial photonic devices utilize the thermoelectric cooler almost exclusively since this is the only way an independently mountable component can be accomplished.

[0003] Recent trends in electronic and especially microprocessor technology continually increase the density of active logic as circuit elements get smaller. One of the most significant limitations preventing further reduction in size is the need to dissipate thermal energy[2,1]. Current technology utilizes fans, heat pipes, active liquid cooling and multiphase heat transfer techniques to minimize the thermal resistance from device junctions to surrounding ambient. While it may be possible to further increase the active junction density by utilizing an external refrigeration system, this approach is not practical for desktop or laptop computing applications. If a micro-refrigeration technology could be developed, highly localized refrigeration or sub-ambient cooling for the most thermally troublesome parts of the electronic circuitry, even within the microprocessor or integrated circuit chip, could be used to dramatically shrink the circuit elements and increase functionality while reducing cost of the system.[2]

[0004] Other applications of a micro-refrigeration system include micro-sensors, such as IR cameras and miniature chemical systems on a chip, cryogenic photonics such as quantum cascade laser devices where the micro-refrigerator could operate in conjunction with a thermoelectric cooler to achieve extremely low cryogenic temperatures, biomedical devices where thermal control of the drug for delivery into the human body is needed, and many others.

[0005] Over the last several years, the application of integrated circuit processing techniques to the design and construction of mechanical, thermal and chemical systems has been developed. This branch of technology is commonly known as Micro-Electro-Mechanical Systems or MEMS. The advantages of this approach to the manufacture of ultra small machines are that the individual devices can be made with many to a single silicon wafer just as in microelectronic integrated circuits and the devices can be made with characteristic dimensions of the order of several microns. This allows the development of machines with tolerances that are much more precise than conventional machining and can be said to be analogous for mechanical devices to the miniaturization revolution that was achieved in microelectronics with the invention of the integrated circuit.

SUMMARY OF THE INVENTION

[0006] A micro-vapor compression refrigeration system on a MEMS chip is invented that maintains the temperature and optical or electrical performance of a photonic or electronic device. This micro-refrigerator operates on the standard vapor compression refrigeration cycle similar to a home refrigerator or air conditioner with choice of working fluid adapted to the application. It is envisioned that the MEMS refrigerator would be fabricated on a submount which would accommodate the photonic or electronic device and provide in-situ refrigeration to the device at temperatures below the surrounding ambient and which would enable integration with other functions such as optical alignment, high speed RF electronic tuning, or optical wavelength monitoring and control directly on the submount.

BRIEF DESCRIPTION OF THE FIGURES

[0007] **FIG. 1** illustrates the basic principle of the invention.

[0008] **FIG. 2** shows the thermodynamic cycle for the invention and relates the refrigerant states to the various entities in **FIG. 1**.

[0009] **FIG. 3** is a perspective view of the main parts of the invention in the preferred embodiment.

[0010] **FIG. 4** shows the various entities that make up the microrefrigerator including section views with the essential features of each element.

[0011] **FIG. 5** illustrates the capability to locally cool the microelectronic or photonic chip using jets of refrigerant.

DETAILED DESCRIPTION OF THE INVENTION

[0012] **FIG. 1** shows schematically the MEMS vapor compression refrigerator on a submount **100**. The refrigerant fluid **101** is compressed in the micro-compressor section **102** and piped **103** to the condenser **104** where it is condensed to a liquid at a temperature slightly above ambient. The liquid is piped **103** to a pressure reducing orifice expander **105** arranged near the evaporator cavity **106**. The photonic or electronic chip **107** is mounted atop an evaporator cavity **106** that has been etched into the substrate material. Heat is conducted from the photonic or electronic chip into the evaporator cavity where it completes the evaporation of the refrigerant and is carried away by the refrigerant fluid. The

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[1] Hecht, Jeff, Understanding Fiber Optics, Second Edition, Prentice Hall, 2002.

[1] Hecht, Jeff, *Understanding Fiber Optics*, Second Edition, Prentice Hall, 2002.

[2] Yeh, L. T., Chu, RC., *Thermal Management of Microelectronic Equipment*, ASME Press, 2002.

warmed refrigerant is piped to the compressor section **102** and the cycle repeats. A thermal sensor **108** such as a thermistor or thermocouple measures the temperature for control purposes. The thermodynamic cycle with the corresponding states of the refrigerant is illustrated schematically in **FIG. 2**. This is a standard vapor compression refrigeration cycle shown on a temperature entropy diagram, that is familiar to those skilled in the art. The refrigerant enters the compressor as mostly or all gaseous vapor at state **1**. It is compressed irreversibly to state **2** by the compressor. State **2***s* illustrates an adiabatic reversible compression process that is isentropic. This would be achieved only in an idealized compressor. Real compressors have less than ideal efficiency resulting in the higher entropy shown in state **2**. The refrigerant then travels through the piping and enters the condenser where it is cooled at constant pressure to state **3** which is all liquid. The liquid travels through the piping to the expander valve and expands adiabatically through the expander valve into the evaporator cavity at state **4**. Heat is withdrawn from the photonic or microelectronic chip causing a constant pressure evaporation of the refrigerant to state **1** and the cycle repeats.

[0013] It is important to note that the state of the refrigerant fluid as it enters the evaporator section is partially liquid and partially gaseous as shown by the state **4** under the refrigerant vapor dome in **FIG. 2**. One of the most efficient heat transfer mechanisms known is that of multiphase heat transfer wherein a phase change from liquid to vapor or vapor to liquid with associated latent heat transfer and vigorous mixing results in heat transfer per unit contact area that is orders of magnitude higher than the comparable single phase heat transfer. This mechanism is advantageously employed in the evaporator and condenser sections to minimize the overall size of the evaporator and condenser and to allow the overall size of the micro-refrigerator to be as small as possible. The size of the evaporator and condenser cavities are further reduced by employing extended heat transfer surfaces or fins to increase the overall heat transfer area. Thus the size of the mounting pedestal for the photonic or microelectronic integrated circuit chip is as small as possible minimizing any parasitic heat transfer from the surroundings to the component mounting surface as is experienced with thermoelectric coolers or larger conventional refrigeration systems.

[0014] It is possible to operate the cycle in reverse in case heating is needed for the photonic or electronic chip. In this case the compressor operates in reverse and compresses the fluid from state **1** to state **2**, which flows to the evaporator cavity. Here the fluid condenses giving up heat to the photonic or microelectronic chip and reaches state **3** at the entrance to the expander valve. The refrigerant then expands across the expander to state **4** and travels through the piping to the condenser where it is heated to state **1** and the cycle repeats. This type of reverse operation may not be as thermodynamically efficient as the normal operation described above, but it is possible.

[0015] **FIG. 3** shows a 3D perspective illustration of the MEMS submount with the refrigerator structures as follows: The submount with micro-refrigerator is constructed of two main MEMS parts including the top part and bottom part. Illustrated is the underside view of the top section **301** of the submount showing the evaporator cavity **302**. Not shown in this view are the thermal enhancement fins in the evaporator cavity. The condenser cavity **303** includes the thermal enhancement fins within the cavity **304**. A recess for the compressor mechanism is shown as **305**. A top view of the top section also shown in perspective illustrates the mounting platform **313** for the photonic or microelectronic chip. The bottom section **307** is shown below with the etched piping recesses **308**, and the bottom recesses forming the evaporator **309**, condenser **310** and compressor **311**. The expander valve is shown as a narrow orifice **312** etched near the inlet to the evaporator.

[0016] An example of one possible embodiment of the compressor section **102** is illustrated in **FIG. 4** with details shown in Section II. The flow cavity **311** is covered with a bimorph membrane **401** consisting of a piezoelectric polymer sheet as for example PVDF **403**. The sheet is metalized in stripe regions on top **402** and bottom **404** with non-metalized regions between each metalized stripe such that the metalized regions are perpendicular to the flow direction. The sheet is bonded to a second PVDF polymer sheet **405**. This bimorph assembly **401** is then bonded to the top of the compressor cavity **311** and when voltage is applied at any point along the membrane a change in shape of the bimorph is created, locally, displacing the fluid from the cavity. Successive voltage applications along the length of the cavity create a peristaltic action and produce flow and increasing pressure in the flow direction. This is illustrated by the deformation in the bimorph **401** shown in Section I.

[0017] An example of one possible embodiment for the evaporator section is shown in **FIG. 4**. The evaporator heat exchanger **106** is composed of a cavity **302** etched in preferably silicon or other MEMS material **301**. The shape of the cavity **302** and pedestal **313** is such that air insulates the cavity and prevents parasitic heat transfer to the surrounding material. Glass **314** and air **309** insulate the bottom of the heat exchanger. The entire structure may be manufactured using standard MEMS wafer processing techniques[3]. In this embodiment, the size of the evaporator is approximately 2 mm×2 mm×1 mm high. The evaporator cavity is provided with extended surface heat transfer fins **306** to allow the cavity to be as small as possible. A similar heat exchanger cavity is shown in **FIG. 4** Section III for the condenser. Here the cavities for heat exchange **303** in top part **301** and **310** in bottom part **307** are also provided with extended surface heat transfer fins **304**. The condenser cavity in this embodiment is approximately 2 mm×4 mm in plan area by about 1.5 mm high.

[0018] The advantage of this configuration is that it can be fabricated and assembled in wafer form using two wafers bonded together to provide a hermetic seal for the refrigerant. In the illustrated preferred embodiment, the two wafers containing many individual refrigerators are bonded together in an environment of refrigerant maintained at an appropriate pressure so that the final assemblies are hermetically sealed with the refrigerant inside.

[0019] Interconnecting piping **308** will be etched into the wafers and the expansion orifice **105** is just a narrowed etched portion of piping **312** near the evaporator cavity **309** entrance.

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[3] Kovacs, Gregory T. A., *Micromachined Transducers Sourcebook*, McGraw Hill, 1998.

[0020] Many potential compressor technologies are available. The exact configuration chosen will depend on the particular application and could be piezoelectric, magnetic, or thermally actuated.

[0021] Overall the size of the entire refrigerator will be less than approximately 10 mm×10 mm by 1.5 mm in the preferred embodiment. This is smaller than previous patents[4] by an order of magnitude.

[0022] One of the advantages of the MEMS implementation of a vapor compression refrigerator is the fact that the refrigerant is in a multiphase gaseous and droplet state as it leaves the expansion orifice. This fact has been shown to greatly enhance the heat transfer and reduce the required surface area thereby allowing a much smaller refrigerator for the same thermal performance[5].

[0023] Typical microelectronic integrated circuits do not have a uniform heat generation over the surface of the chip but often have localized regions of much greater thermal dissipation corresponding to very dense and very active circuit elements with the IC chip. The greatly enhanced thermal performance of droplet spray multiphase cooling over a small area may allow local cooling of hot spots within the integrated circuit chip. An arrangement of refrigerant jets allows cooling of the hottest spots permitting much denser circuits and enabling improved electrical performance. A preferred embodiment of this principle is shown in **FIG. 5**. The integrated circuit microelectronic chip **107** is illustrated mounted on the evaporator **106** pedestal **502** with various hot spots shown by the darker shading **503**. Cooling jets of refrigerated multiphase vapor droplet refrigerant **101** are directed via a plenum chamber **504** with precisely located orifices **505** to the most intense hot regions requiring cooling thereby allowing much greater densification of the circuit elements on the microelectronic chip and potentially faster performance of the electronic device.

I claim:

1. A micro-refrigerator operating on the vapor compression refrigeration cycle that is less than 10 mm×10 mm×1.5 mm in size and is fabricated using MEMS processes.

2. The evaporator section substantially as shown in **FIG. 4** allowing the direct mounting of photonic or microelectronic integrated circuit chip for cooling.

3. The evaporator arrangement of claim 2 wherein the interior of the chamber is provided with etched fins for efficient heat transfer to the refrigerant.

4. The evaporator arrangement of claim 2 wherein the coolant is supplied in multiphase droplet/vapor mixture for greatly enhanced heat transfer and advantageously smaller evaporator volume.

5. The evaporator section of claim 2 wherein the embodiment of the chamber is thermally insulated by air and glass to prevent parasitic thermal leakage to the surrounding material.

6. The condenser section substantially as shown in **FIG. 4** with extended surface fins for minimum condenser volume and allowing dissipation of heat to the surroundings.

7. The condenser section of claim 6 wherein the heat exchanger is thermally attached to a heat sink to aid in thermal dissipation to the surrounding ambient.

8. The condenser section of claim 6 wherein the multiphase heat transfer to the condenser surface minimizes the condenser volume.

9. A compressor section that is fabricated with MEMS processes allowing the piezoelectric, electromagnetic or thermal actuation to compress the refrigerant fluid to working pressure.

10. The compressor section of claim 7 wherein the compressor is actuated by a piezoelectric polymer such as PVDF arranged in a bimorph construction with metalization allowing a peristaltic pumping action with so sliding contact parts minimizing wear.

11. MEMS etched interconnecting piping allowing the refrigerant to circulate between the evaporator, compressor, condenser and expander orifice.

12. MEMS etched orifice in the interconnecting piping of claim 11 wherein the pressure drop is regulated to the evaporator chamber.

13. A plenum chamber arrangement as illustrated in **FIG. 5** that provides localized cooling jets of refrigerant to the hottest regions of the photonic or microelectronic integrated circuit chip.

14. The micro-refrigerator of claim 1 wherein the compressor section is operated in reverse to provide heating to the photonic or microelectronic integrated circuit chip.

15. The micro-refrigerator of claim 1 wherein the mounting location for the photonic or microelectronic chip is provided with an electrical resistance heater to allow independent control of the chip temperature without changing the refrigerator operating parameters.

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[4] Beebe, D., Bullard, C., Philpott, M., Shannon, M., "Active compressor vapor compression cycle integrated heat transfer device," U.S. Pat. No. 6,148,635, November 2000.

[5] Schlager, L. M., Pate, M. B., Bergies, A. E., "Evaporation and Condensation Heat Transfer and Pressure Drop in Horizontal, 12.7 mm Microfin Tubes With Refrigerant 22," *Journal of Heat Transfer*, Volume 112, pp. 1041-1047, 1990.