Micromachined acoustic ejector device for generating a jet stream using a Helmholtz resonator, applications for the ejector in microflight, active heat sinking and fluid pumping and methods of manufacturing the resonator and ejector device. The resonator comprises a resonant diaphragm and a drive electrode to operate on a volume inside a cavity of the resonator. The resonance frequency of the resonator is correlated or matched to the resonance of the cavity. The volume is forced out of the resonator through a throat, with the throat being variable through the use of another diaphragm. A shroud and a cover can direct flow to the resonator. An array of the ejectors can be fabricated. A heater can vary the resonance inside the cavity as can another diaphragm vary the geometry of the cavity.
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MICROMACHINED ACOUSTIC EJECTORS AND APPLICATIONS TO MICRO
THRUSTERS, ACTIVE HEAT SINKS AND FLUID PUMPS

This invention was made with United States government support awarded by the
National Science Foundation under Grant # ECS-925-7400. The United States government
has certain rights in the invention.

This application is based on United States Provisional Patent Application serial
number 60/095,393, filed August 5, 1998.

Field of the Invention

The field of the invention pertains to jet flow generation and in particular, a device to
realize jet stream generation using MEMS (MicroElectroMechanical Systems) technology
and the method of use of the device for propulsion, pumping and heat removal applications.
The invention also pertains to the method for fabrication or micromachining to create the jet
stream generation device.

Background of the Invention

Synthetic jets have been demonstrated in micro scale, but none of those jets operate in
the resonance mode. Although, jets have been used for actuation and flow control, micro
jets have not before been demonstrated for propulsion. Significant research effort has been
expended to produce more efficient heat removal schemes from integrated circuit chips. One
of the recent promising discoveries is micro channel based heat sinks. In these devices,
microchannels are formed in a substrate and a fluid is subsequently forced through them
cooling down the whole device and structures adjacent to it. However, these devices require the use of an external power source to pump the fluid through the microchannel.

Thus, more efficient jet generation devices and methods are needed. Some of the materials listed below discuss the pertinent prior art technologies, such as applications with Helmholtz resonators and various devices, micro heat sinks, micro pumps and synthetic jet actuators.

US Patent No. 5758823 describes an acoustic streaming based synthetic jet actuator which can be micromachined and its applications in flow control and such.

US Patent No. 5710395 discusses the structure of a loudspeaker system having a capsule shape with truncated ends utilizing a Helmholtz resonator for active frequency control.

US Patent No. 4602245 shows a general purpose modular acoustic signal generator. In this device a piezoelectric acoustic generator disc is mounted in such a fashion to make two separate Helmholtz resonance cavities.

US Patent No. 5371330 teaches a synchronized acoustic source for generation of seismic waves. Acoustic resonators are used here to produce a near zero impedance condition at each end of the apparatus.

US Patent No. 4858717 describes an acoustic convective system used for cooling or heating small components and circuit boards by creating a standing sound field using a reflector and the subsequent production of acoustic streaming.

US Patent No. 5457342 teaches a modular heat sink design consisted of a conductive plate, a Peltier effect cooling unit and a juxtaposed fan assembly passing flow over the attached heat radiator.

US Patent No. 5529115 shows a cooling device for integrated circuits having an internal cooling conduit taking advantage of coolant vaporization for heat sinking.

US Patent No. 5386143 discusses a high performance integrated circuit cooling system operating based on transfer of vaporized coolant through porous ceramic and the subsequent condensation under a plurality of heat transfer fins.

US Patent No. 4399484 describes the application of direct jet stream for localized cooling on integrated circuit boards through a modified housing design.

US Patent No. 5016090 shows the embodiment of cross-hatched coolant flow through two sets of channels perpendicular to each other and achievement of high performance cooling.

US Patent No. 5520522 discusses the structure and valve arrangement of a micro pump actuated by magnetostrictive or electrostrictive means.

US Patent No. 5096388 describes another micropump design implemented in a semiconductor substrate and integrated with the relevant channels. The fluid motion is achieved by a wave like motion in a semiconductor diaphragm.
Relevant Papers:
D.J.Coe, M.G.Allen, B.L.Smith, A. Glezer, "Addressable micromachined jet arrays", presented at Transducers '95/Eurosensors IX
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Summary of the Invention

A device and method for generation of jet streams in microscale is disclosed. The device comprises a resonator with a resonant diaphragm and a geometrically variable cavity which may incorporate a heater, a perforated drive electrode or plate to operate the diaphragm and one or more throats (which may also be geometrically variable), through which the jet/s is/are produced. The miniaturization of an array for creating jet streams is of great importance to the invention. The method for jet generation takes advantage of acoustic streaming, resonance in a Helmholtz cavity and jet entrainment and augmentation. Shown here is a novel system for thrust generation in microscale. Also hereshown is a novel complete integrated system capable of active heat sinking without any need for an external fluid actuation source.

Applications for which the device for generation of jet streams in microscale is appropriate encompass:
a) A micro airborne vehicle/platform which uses an array of micro acoustic ejectors as a means for thrust generation and control;
b) A micro air pump; and
c) A micro active heat sink to be used for cooling of Integrated Circuit chips.
Also disclosed herein are novel methods for manufacturing the device for jet stream generation in microscale using micromachining techniques by assembling resonators to chips in a large array or by integrating resonators at the chip level. The methods are easy and simplify the manufacturing process. Fewer and simpler steps are necessary for the manufacturing of the device.

Jet stream generation and means to realize jet stream generation using MEMS technology and methods for micromachining to create the jet stream generation device comprise the invention. By taking advantage of resonance phenomenon and nonlinear flow behavior, this invention allows for efficient generation of jet streams which can be scaled to the micro domain and permits the formation of millimeter sized devices for use in a number of applications. This invention surpasses conventional jet technology in efficiency and robustness, power dissipation, and size and weight.

Implementation of flow entrainment and augmentation makes this jet more effective than other jet generators operating at the same scale. The fabrication technology developed to manufacture the device is compatible with standard Integrated Circuit processing techniques which thus allows integration with smart sensors and circuits. The device can be batch fabricated which lowers the cost of production compared to other known methods. The resonators can be integrated at chip level. Alternately, large arrays consisting of hundreds of jets can be manufactured which then produce a larger level of force and thrust for use in a number of applications. The disclosed jet stream generation technology can be implemented as a part of a more elaborate system.

The invention is applicable to three major application areas, but other application areas could be utilized. The three major application areas are namely: application of an array of micromachined acoustic ejectors for propulsion and control of micro vehicles, a micro gas pump using the jet flow generator, and a micro active heat sink device. No external flow actuation source is needed for the micro active heat sink, nor does the micro active heat sink have any rotating/sliding parts and the micro active heat sink can be attached to any integrated circuit to achieve efficient and reliable cooling.

**Brief Description of the Drawings**

FIG. 1 illustrates the structure of an acoustic ejector consisting of an array of resonators hybrid mounted inside an injection-molded shroud;

FIG. 2 illustrates a cross-sectional view of a micromachined Helmholtz resonator;

FIG. 3 illustrates a cross-sectional view of a micromachined Helmholtz resonator with refinements.
Description of the Preferred Embodiment

Part I: Micromachined Acoustic Ejector

FIG. 1 depicts a device 10 for generating a jet stream by acoustic streaming employing a micromachined acoustic ejector 12 and method for efficient generation of jet streams. The device 10 is comprised from a resonator/s 14 such as a Helmholtz resonator fitted interiorly to a shroud 16 with a top cover 18 for directing flow to the resonator 14. The top cover 18 operates as a top port to direct air flow into the ejector 12. The profile of the cover and the shroud are blended with each other and with the jet stream to prevent flow separation.
The shroud 16 partially surrounds the resonator 14. The shroud 16 and the top cover 18 can be formed from injection molded plastic or other suitable material. The shroud 16 has a resonator well 20 for placement of the resonator 14 thereto and a connector groove 22 for placement of a connector (not shown) to the resonator. However, it is to be understood that the resonator can be fully integrated into the device at the initial manufacturing point and not require a separate assembly step. A jet stream 24 is generated by the resonator 14 and a cumulative jet stream 24' is generated through the device 10. The cumulative jet stream 24' is generated by amplification through the use of multiples of the resonator 14 in conjunction with the top cover 18 and the shroud 16. The amplification of the jet stream results in large thrust augmentation and large flow augmentation. Thrust augmentation impacts propulsion and flow augmentation impacts fluidic pumping and heat sinking. Accordingly, it is to be understood that multiples of the resonator 14 and/or multiples of the device 10 can be effectively employed as will be discussed below.

The resonator 14 is better depicted in FIG. 2. The resonator 14 comprises a vibrating diaphragm 26 of silicon substrate operable by a perforated drive electrode 28 to produce fluid motion inside a cavity 30. The vibrating diaphragm 26 rests on a silicon rim 27 that supports the vibrating diaphragm 26 and a cavity 30. The diaphragm 26 is activated by application of a voltage to the perforated drive electrode or perforated plate 28 adjacent to the diaphragm 26. The cavity 30 is formed from the vibrating diaphragm 26 and a lower layer 32 of glass or silicon substrate or other suitable substrate material. The fluid displacement is amplified by using the Helmholtz resonator 14 and in turn causes an intense acoustic field 34 through the resonator orifice 36 to the exit 38 of the throat 40 (FIG. 3). A sensor 42 is located near the exit 38. The acoustic field 34 induces a jet stream 24 through acoustic streaming. The jet stream 24 can be modified through the resonator 14 by the use of a heater 44 and a diaphragm 46 in the cavity 30 and a diaphragm 48 near the throat 40.

The present invention exhibits efficiency of jet generation which by operation in the resonance mode exceeds conventional jet engines. Especially in terms of power to thrust ratio and thrust per unit area, the resultant figures for the invention, ~100 meters per second and ~1000 Pa respectively, show a remarkable improvement over other existing large scale jet engines and this is gained mainly by using an optimized structure for momentum transfer enhancement with flow entrainment and augmentation.

Unlike other jet generators, the micromachined acoustic ejector 12 is suitable for scaling to very small dimensions and thus a myriad of applications in microelectromechanical systems is perceivable for it. The dimensions for a micro acoustic ejector can range from a few microns up to centimeters depending on the application. A number of ejectors can be put into an addressable array to form an acoustic thruster and be used as a complete propulsion unit. The high air velocity at the exit port of the device makes it suitable for heat transfer applications as discussed hereinbelow in part IIc.
Micromanufacturing methods for manufacturing these devices fabricate the Helmholtz resonator 14 in a two wafer process. The first or top wafer 50 contains the resonant diaphragm 26 that actuates the amplified pulsating jet stream 24 and the upper cavity portion 52 of the cavity 30 and the throat 40, while the second or bottom wafer 54 contains the lower cavity portion 56 of the cavity 30.

Turning now to FIGs. 4 A - 4 S, a number of novel techniques are used for the micromachining to form the structure of the top layer or wafer 50. FIG. 4 A depicts a blank substrate 58. A silicon dioxide layer 60 is then added (FIG. 4 B). The diaphragm 26, electrical contacts and hot wire anemometers are defined through a shallow boron diffusion process via the silicon dioxide mask 60 at the beginning of the process on the top wafer. A photo resist layer 62 is then added (FIG. 4 C). Deep trenches 64 (FIG. 4 D) are etched and the photo resist layer 62 is removed 66 (FIG. 4 E) and subsequently the deep trenches 64 are treated with a boron diffuser 68 (FIG. 4 F) and are filled with a combo layer of dielectrics (silicon dioxide, silicon nitride and silicon dioxide) and polysilicon 70 using Chemical Vapor Deposition (FIG. 4 G). The deep trenches 64 define the thick silicon rim which supports the diaphragm and have a certain geometrical pattern. The dielectric and polysilicon layer 70 thickness over the diaphragm region is trimmed 72 to achieve stress compensation (FIG. 4 H). In use, diaphragm 26 is actuated electrostatically by application of a voltage across the actuator cavity and its movement generates the necessary flow displacement in the resonance cavity.

Another dielectric layer 74 caps the deep trenches 64 (FIG. 4 I). A portion 76 of the earlier applied dielectric layer 74 is exposed (FIG. 4 J). An orifice to the cavity will be defined by later removal of region 78 (FIG. 4 K). A metal layer 80 is deposited (FIG. 4 L). Then a polymer layer 82 is deposited (FIG. 4 M) creating via holes 86 and setting the height 84 of the throat to be created later. A gold layer 88 is deposited (FIG. 4 N) followed with a seed layer of titanium and gold 90 (FIG. 4 O). Another layer of polymer 92 is deposited (FIG. 4 P). Thereafter, a layer of gold 94 creating the ceiling of the throat is deposited (FIG. 4 Q) and all the sacrificial materials are removed including all polymers, sacrificial polysilicon and most of the single crystal silicon (FIG. 4 R). FIG. 4 S shows the completed resonator 14 attached to the lower wafer. The bottom wafer 54 is fabricated separately and the resonance cavity is formed by using a patterned Cr/Au mask formation followed by HF nitric etch in glass or EDP etch on silicon wafers or a multiplexed reactive ion etching. After the completion of the bottom 54 (or second wafer), the two wafers are bonded together and the structure of the device 10 is complete with the resonator/actuator 14, the cavity 30 and the throat 40 (FIG. 6).

A number of resonators can be configured to form the ejector. Also disclosed herein are manufacturing methods for fabrication of the micro acoustic ejectors. The first method which is a hybrid approach needs hand assembly; however, it provides shorter design iteration
cycles. The resonator body consists of two parts made by injection molding. The bottom part contains cavities for fitting resonator units, the shroud and vias for connector routing. The flow path is completed by the top part which has the form of a nozzle. Micro acoustic ejectors are put into arrays to build thruster units. This approach is more elaborated in the micro air vehicle section.

The dimensions of the device can be changed according to various design criteria. The resonance frequency of the diaphragm can be correlated and/or matched with the resonance frequency of the resonance cavity. The resonance frequencies can be actively modified by a number of methods. A DC bias can be applied to the diaphragm or a secondary diaphragm can be used to change the volume of the cavity and thus change the acoustic resonance frequency. Also temperature variations can be used to tune the resonance frequencies. The resonators are connected by silicon cables and can be activated via the signal lines. Flow and temperature sensors are integrated in the top wafer and provide data for active control of the resonator.

FIGS. 5 A through 5 T depict a multiple layer chip. FIGS. 5 A - 5 G show the fabrication sequence of a MACE actuator or resonator, while FIGS. 5 H through 5 K illustrate the fabrication of a MACE bottom wafer 96 including an actuator or resonator 14 derived from FIG. 5 G (with the actuator 14 shown in smaller scale) and FIGS. 5 L through 5 T illustrate the fabrication sequence of MACE top wafer 98.

The fabrication sequence is now described in more detail. The integrated fabrication method for the micro acoustic ejectors uses two wafers. The first wafer holds the actuation part and a section of the flow path. The process starts with selective boron diffusion to define the diaphragm contact electrode (FIG. 5 A). Then a silicon dioxide layer is deposited and patterned (FIG. 5 B). The silicon underneath the silicon dioxide is wet etched through holes in the upper layer (FIG. 5 C) and then a second diffusion step is performed to complete one of the actuator plates (FIG. 5 D).

Thereafter, Low Pressure Chemical Vapor Deposition is used to seal the actuator cavity (FIG. 5 E) and a silicon nitride layer (FIG. 5 F) is subsequently deposited for stress compensation. The actuators are completed by deposition and patterning a gold layer (FIG. 5 G) which defines the second plate for the electrostatic actuator and also electrical contact to the boron doped regions. Processing on the bottom wafer is continued on the other side by patterning the silicon dioxide layer and a deep etch step which opens a flow path which is as deep as the wafer itself. Profile of this channel is modified to get the optimal flow entrainment/augmentation characteristics.

The process on the second wafer starts with patterning a silicon oxide layer (FIG. 5 H) with actuators embedded on the opposite side of the wafer. Cavities are etched through this oxide mask which define the size of the resonance cavity (FIG. 5 I). A thermal silicon dioxide layer is grown and patterned and a through wafer etch is performed (FIG. 5 J). Then the top silicon dioxide layer (FIG. 5 K) is removed with reactive ion etching and the profile of
the flow path is shaped to achieve high performance flow characteristics. A deep boron diffusion step is performed to ensure the profile integrity after the EDP step. The EDP step is performed next and determines the length of the throat for the resonance cavity and also the volume of the resonance cavity. Both wafers are ready at this step and they are bonded to form the complete device (FIG. 6).

Based on the lateral design of the mask set the geometry of the ejector can be changed to meet various flow requirements. The processing sequence of the bottom wafer can be integrated with a conventional CMOS (Complementary Metal Oxide Semiconductor) process by postponing the gold deposition for the actuator till after the completion of the CMOS process. In this case an aluminum line from the CMOS process can be used to complete the actuator structure. It should be noted the circuitry should be fabricated in the same side as the actuator since a silicon dioxide layer is used on the other side as masking layer for deep dry etching of the substrate.

The ability to integrate CMOS circuitry gives this process a tremendous advantage for full scale system implementation and integration. This is a necessity for Micro Air Vehicle fabrication which is discussed hereinbelow. It is also envisioned that other silicon based micro sensors can also be implemented on the same wafer and interfaced using on chip circuitry.

FIGs. 7 A and 7 B depict an embodiment of the invention having an array of ejectors. The process flow to fabricate the device is shown in FIGs. 7 A-1 through 7 A-5 using MEMS technology. The method for fabricating an acoustic ejector device starts with a silicon wafer upon which an oxide layer is grown followed by patterning the oxide layer with a photoresist layer. Then boron diffusion is performed through the oxide layer and the patterned oxide layer is etched away. An oxide and a polysilicon layer are added subsequently and are patterned. Then three new layers of dielectric (nitride, oxide and polysilicon) are deposited over the patterned first two layers followed by doping of a polysilicon layer. The boron doped polysilicon layer is added over the three layers of dielectric. The boron doped polysilicon layer over the three layers of dielectric is patterned and a second two layers of dielectric (oxide and nitride) are added over the boron doped polysilicon layer. The second two layers of dielectric over the boron doped polysilicon layer are patterned and then a gold layer is sputtered over the second two layers of dielectric. Thereafter, the gold layer is patterned and any layers at the bottom of the wafer are etched away. Then the throat area of the device is deep etched and a glass wafer is bonded to the top layer, which is the boron doped silicon layer. To complete the fabrication, the silicon wafer is etched away. Suitable shaped top and bottom pieces (not shown) are added to complete the ejector.

A full wafer photograph (FIG. 7 B) shows four quadrants with multiple ejectors and with each ejector having six resonators surrounding the ejector in the center. The diaphragm resonance frequency of the resonators surrounding the ejector is correlated or matched to the
cavity resonance frequency. Individual resonators are deployed along the quadrant line. The individual resonators are operable off-resonance and can be used for testing and for additional jet stream generation. **FIG. 7 C** illustrates a Scanning Electron Microphotograph of an individual ejector. The ejector can operate in the range of 120 kHz.

**Part IIa: Micro Airborne Vehicle/Platform**

A Micro Airborne Vehicle/Platform (hereafter referred to as the Micro Air Vehicle) 100 is shown in **FIG. 8** which can be scaled down to micro scale domain. The micro air vehicle 100 takes advantage of the superior jet characteristics obtained from application of the micro acoustic ejectors described above.

The micro air vehicle 100 consists of a disc-shaped body which is symmetrically covered with arrays 102 of micro acoustic ejectors 12. The control unit and the power source are located in the center of the disc-shaped body. The power and signal lines are routed throughout the disc-shaped body to distribute/collect the relevant data and provide energy for the thrusters. The vehicle 100 takes off vertically and the horizontal movement is achieved by asymmetric jet generation. The difference in momentum transfer to the flow creates a coupling force which tilts the whole micro air vehicle. This tilting in turns enable a horizontal force component to be applied to the micro air vehicle 100 and thus movement is achieved. Micro scale flight is shown for the first time here.

The micro air vehicle 100 can be hand assembled after fabrication of individual ejector units or be batch fabricated by using a modified micromanufacturing process for micro acoustic ejectors. In the integrated approach, since the devised fabrication process is designed to be CMOS compatible, an array of sensors can be integrated on board. Also the control circuitry is positioned at the center of the micro air vehicle 100 (the control dome) by standard CMOS process. Thus the manufacturing process is fast and the production cost is lower. The power can be transferred to the structure via a microcable or in case of free flight it can be provided by an on board battery (not shown), such as a lithium battery or other power source.

**Part IIb: Micro Air Pump**

A micro pump 104 is shown in **FIG. 9** A as having a housing which provides microchannels for air flow and an air actuating unit or resonator 14. Air is moved inside the microchannels by taking advantage of flow entrainment. A resonator 14 is positioned in each microchannel. The output jet from the resonator entrains air in the microchannel and thus a net fluid flow is achieved.

The micro pump 104 provides a significant design flexibility and can be tailored for high flow or high pressure rise applications on demand. In case of use of a micro acoustic ejector structure, pressure rises as high as 50 mm of water or flow rates as high as 63 cubic
feet per minute at 34 Watts are achievable. The pump can be used as a part of an integrated microfluidics system and with minor changes can perform both in liquid and gas environments.

Micromanufacturing process for the implementation of the micro pump 104 are shown in FIG. 9 B. The process involves three layers which are processed separately and bonded upon completion. The first or the bottom layer contains the air actuation module. The air actuation module is formed by fitting a micro acoustic resonator 14 in a cavity etched in the bottom layer. The micro acoustic resonator 14 is formed by a method similar to what is described in part one. The air actuation module provides a strong pulsating jet stream which through flow entrainment provides fluid pumping.

The second or the middle layer is formed from silicon (by deep etching using reactive ion etching) or metal (by electroforming, metal forming) and contains the microchannels 106 guiding the fluid through the micro pump and also the input ports and output ports for the micropump. The channel heights range from a few microns to a few centimeters and the length of the structure is variable based on the pumping requirement. The bottom and top of the microchannels are flat and the walls are formed in such a way to facilitate the fluid motion and are treated for smoothness. At the inlet ports, the channels resemble a nozzle and at the outlet the microchannel have a shape resembling a diffuser.

Finally, the third layer completes the micropump and in the case of tall channels, closes the top end of the channels. The third layer forms a top and encloses the tall channels and can include via holes to provide vertical access to the microchannels and thus creates vertical input/output ports. Signal and power lines are routed through the etched grooves in the micropump for power distribution and control of individual micro acoustic resonators in the case of a multiple flow actuator pump.

Part II c: Micro Active Heat Sink

As mentioned in the prior art section, there has been a significant research effort in order to produce more efficient heat removal schemes from integrated circuit chips. One of the recent promising discoveries is micro channel based heat sinks. In these devices, microchannels are formed in a substrate and a fluid is subsequently forced through them cooling down the whole device and structures adjacent to it. This calls for the use of an external power source to pump the fluid through the microchannel.

Relevant micromanufacturing methods have been developed for batch fabrication of the heat sink. Each heat sink unit is packaged separately and is attached on top of an integrated circuit chip through a socket. The cooling unit consists of multiple sublayers. Each sublayer in turn consists of three layers housing a flow actuation unit and microchannels. Cavities are etched in the first layer and Helmholtz resonators are fitted in the cavities creating the flow actuation units. Helmholtz resonators can be fabricated separately by the method
mentioned in part I or be an integral part of the process for the first wafer. The resonators are
correlated by power and signal lines run through etched grooves in the structure and can be
addressed individually.

Embedded flow and temperature sensors provide active flow control data if necessary. The
data can be used to maintain the temperature of the whole structure or sustain a
predefined temperature gradient across the structure to expand heat sinking.

The second layer is mounted on top of the first layer by bonding and contains a pattern
of microchannels. Each microchannel can overlap with one or more micro acoustic resonator
units. The channels are formed in metal or semiconductor by deep etching or metal forming.
The microchannel height ranges from a few microns to a few centimeter and the microchannel
length is determined by the length of the integrated circuit package to be cooled. The walls of
the microchannel have a vertical profile chemically treated for smoothness and facilitation of
the fluid flow. The lateral profile of the microchannels resembles a nozzle shape at the inlet
and a diffuser shape at the outlet and varies across the area of the device.

Finally, the third layer completes the structure by closing the high aspect ratio
microchannels. The third and last layer also contains the cavities for the next stage of the
structure. A number of sublayers can be stacked to form a complete device. The sublayers are
connected by vertical leads and can be operated individually if necessary. The package base is
formed from a highly conductive material to enhance the heat transfer capabilities of the
structure. The unit is a self sustaining device and does not require external pumps or any
other peripheral microfluidic devices.

Here shown is a novel complete integrated heat sink capable of active heat sinking
without any need for an external fluid actuation source. The active heat sink 108 acts as an
independent active unit which consists of embedded microchannels (FIG. 10 A) and integrated
micro acoustic resonators 14 or micropumps 110 (FIG. 10 B) to force fluid through the
microchannels. The coolant used here is air and this provides a remarkable reliability
superiority over liquid coolants and at the same time provides enough heat sinking capacity for
use on high power high performance integrated circuit chips. It should be noted also that there
is no sliding or rotating part in the system which in turn helps the long term reliability of the
system.

A Scanning Electron Microphotograph of a micro acoustic resonator according to the
invention is depicted in FIG. 11. Via holes in the perforated back plate 28 and the exit 38 of
the throat 40 of the resonance cavity and the hot wire anemometers are shown. Further, the
hot wire anemometer flow sensors can be used for active performance control of the device.
FIG. 12 is a Scanning Electron Microphotograph of the exit 38 of the throat 40 of a micro
acoustic resonator. The resonator is designed to operate in the resonance range of 30-50
kHz with low viscous losses.
Having described the invention, many modifications thereto will become apparent to those skilled in the art to which it pertains without deviation from the spirit of the invention as defined in the appended claims.
Claims

1. A device for generating a jet stream by acoustic streaming comprising:
   a resonator having a lower layer, a resonant diaphragm having a resonance frequency
   when resonated, the resonator having a resonance frequency when resonated, said resonant
diaphragm partially engaging with the lower layer, said lower layer and said resonant
   diaphragm forming a cavity having a geometric shape;
   a perforated drive electrode adjacent and partially engaging with said resonant
diaphragm,
   at least one throat having a geometric shape and an exit, said at least one throat being
fluidly connected with said cavity whereby when the resonator is activated, a jet stream is
produced and directed from the exit of at least one throat of the resonator.

2. The device for generating a jet stream by acoustic streaming according to
   claim 1 further comprising:
   a shroud having a profile and an interior, said resonator being locatable to the shroud
   and having at least the exit of the throat inside the shroud.

3. The device for generating a jet stream by acoustic streaming according to
   claim 2 further comprising:
   a cover, said cover being placeable to said shroud.

4. A method for fabricating an acoustic jet device for producing a jet stream, the
device having a throat, the method comprising the following steps:
   growing an oxide layer on a silicon wafer;
   applying a photoresist layer over the oxide layer on the top of the silicon wafer;
   patterning the oxide layer with a photoresist;
   applying boron diffusing over the patterned oxide layer,
   etching the patterned oxide layer away on the top of the silicon wafer;
   applying a first at least one layer of dielectric over the boron diffuser on the silicon
   wafer,
   patterning the first at least one layer of dielectric over the boron diffuser on the top of
   the silicon wafer;
   applying a second at least one layer of dielectric over the first at least one layer of
dielectric on the silicon wafer;
   applying a boron doped polysilicon layer over the second at least one layer of
dielectric;
patterning the boron doped polysilicon layer over the second at least one layer of dielectric on the top of the silicon wafer,
applying a third at least one layer of dielectric over the boron doped polysilicon layer,
patterning the third at least one layer of dielectric over the boron doped polysilicon layer on the top of the wafer,
applying a gold layer over the third at least one layer of dielectric on the top of the wafer,
patterning the gold layer over the third at least one layer of dielectric on the top of the wafer;
etching layers at the bottom of the wafer;
deep etching the throat area on the top of the silicon wafer,
bonding a glass wafer to the boron doped polysilicon layer at the top of the silicon wafer; and
etching away the silicon wafer and the first at least one layer of dielectric.

5. A method for fabricating a device for producing a jet stream, the device having a throat, the method comprising the following steps:
adding a silicon dioxide mask layer to a blank first substrate;
applying a first boron diffusion through the silicon dioxide mask;
adding a photo resist layer forming a certain geometry;
etching trenches through the photo resist layer;
removing the photo resist layer;
treating the trenches with a second boron diffusion;
filling the trenches with at least a first layer of dielectric and a layer of polysilicon,
trimming the at least first layer of dielectric;
capping the trenches with at least a second layer of dielectric,
exposing a portion of the at least first layer of dielectric;
depositing a metal layer;
depositing a first polymer layer over the metal layer,
depositing a first layer of gold;
depositing a seed layer of titanium and gold;
depositing a second layer of polymer;
depositing a second layer of gold;
removing the first and second layer of polymer, the layer of polysilicon and part of the substrate;
patterning a second blank substrate with a chromium and gold mask;
etching the second wafer to create a cavity; and
bonding the first and second wafer together.

6. A method for generating a jet stream produced by the device according to claim 1 comprising the following step:
   resonating the resonator to produce a resonance frequency.

7. A method for generating a jet stream produced by the device according to claim 6 comprising the following step:
   correlating a resonance frequency of the resonator with a resonance frequency of the resonant diaphragm.

8. A method for generating a jet stream according to claim 6 further comprising the step:
   employing at least one shroud with the device.

9. A method for generating a jet stream according to claim 6 wherein the resonance frequency can be actively controlled by the following step:
   employing a second diaphragm, wherein the cavity has a volume and the volume of the cavity being changeable by said second diaphragm.

10. A method for generating a jet stream according to claim 6 further comprising the following step:
   varying the resonance frequency of the resonator by at least one heater.

11. A method for generating a jet stream according to claim 6 further comprising the following step:
   varying the resonance frequency of the resonator by changing the geometric shape of the throat by means for moving the diaphragm.

12. A method for generating a jet stream according to claim 8 further comprising the following step:
   blending a profile of the shroud with the exit of the resonator to prevent flow separation of the jet stream at the shroud.
13. A method for generating a jet stream by operating resonators having at least
the exit of said throat of said resonators in the shroud according to claim 2 further comprising
the following step:
operating at least one resonator with a phase difference to achieve better jet stream
amplification

14. A method for generating a jet stream according to claim 11 further comprising
the following step:
modifying the geometric shape of the resonator to improve the jet stream
amplification

15. A method for generating a jet stream according to claim 10 wherein the
resonator having a second chamber, the method further comprising the following step:
pressing the resonant diaphragm against the second chamber, said second chamber
holding a vacuum level, with said drive electrode locatable inside said second chamber.

16. A method for generating a jet stream according to claim 8 further comprising
the following step:
moving the resonant diaphragm against a perforated plate.

17. A method for generating a jet stream according to claim 8 further comprising
the following step:
embedding a flow sensor in the resonator for at least one of monitoring flow
amplification, closed loop flow control and feedback control.

18. A method for generating a jet stream according to claim 1 further comprising
the following step:
positioning a flow sensor downstream from the throat of the resonator, wherein said
flow sensor being an integrated hotwire anemometer.
19. A method for manufacturing a device for generating a jet stream comprising at least one of the following steps:
fabricating multiples of resonators according to claim 1 in a large array.

20. A method for manufacturing a device for generating a jet stream comprising at least one of the following steps:
fabricating multiples of resonators according to claim 2 in a large array.

21. A method for manufacturing a device for generating a jet stream comprising at least one of the following steps:
fabricating multiples of resonators according to claim 3 in a large array.

22. A device for pumping air comprising:
at least one microchannel having a converger for converging a flow of air, the flow of air being channeled through the microchannel and at least one diffuser for diffusing the flow of air, and
a device according to claim 1 for generating a jet stream, whereby the device for generating a jet stream creates a pressure rise across the device for pumping air and causes a flow of air through the at least one microchannel.

23. A device for pumping air comprising:
at least one microchannel having a converger for converging a flow of air, the flow of air being channeled through the microchannel and at least one diffuser for diffusing the flow of air, and
a device according to claim 2 for generating a jet stream, whereby the device for generating a jet stream creates a pressure rise across the device for pumping air and causes a flow of air through the at least one microchannel.

24. A device for pumping air comprising:
at least one microchannel having a converger for converging a flow of air, the flow of air being channeled through the microchannel and at least one diffuser for diffusing the flow of air, and
a device according to claim 3 for generating a jet stream, whereby the device for generating a jet stream creates a pressure rise across the device for pumping air and causes a flow of air through the at least one microchannel.
25 A device for heat sinking comprising at least one microchannel and the device according to claim 1.

26 A device for heat sinking comprising at least one microchannel and the device according to claim 2.

27 A device for heat sinking comprising at least one microchannel and the device according to claim 3.

28 A device for generating a cumulative jet stream by acoustic streaming comprising:
   a resonator, having a lower layer, a resonant diaphragm having a resonance frequency when resonated, the resonator having a resonance frequency when resonated, said resonant diaphragm partially engaging with the lower layer, said lower layer and said resonant diaphragm forming a cavity having a geometric shape;
   a perforated drive electrode adjacent and partially engaging with said resonant diaphragm,
   at least one throat having a geometric shape and an exit, said at least one throat being fluidly connected with said cavity and a first jet stream issuing from the exit of the throat; and
   a shroud having a profile and an interior, said resonator being locatable to the shroud and having at least the exit of the throat inside the shroud, whereby when the resonator is activated, the first jet stream is produced and directed from the at least one throat of the resonator with the first jet stream merging with and augmenting a second jet stream.