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(71) Applicants: IC SENSORS, INC. [US/US]; 1701 McCarthy Boulevard, Milpitas, CA 95035-7416 (US). BAXTER INTERNATIONAL INC. [US/US]; One Baxter Parkway, Deerfield, IL 60015-4633 (US).

(72) Inventors: JERMAN, John, H.; 3056 Ramona Street, Palo Alto, CA 94306 (US). TOTH, Ronald, E.; 444 Rock Hall, Grayslake, IL 60030 (US). WINCHELL, David, A.; 531 Circle Drive, Fox Lake, IL 60020 (US). PENNINGTON, David, W.; 38 S. Hawthorne Lane, Fox Lake, IL 60020 (US).

(74) Agents: KLIVANS, Norman, R. et al.; Skjerven, Morrill, MacPherson, Franklin & Friel, Suite 700, 25 Metro Drive, San Jose, CA 95110 (US).

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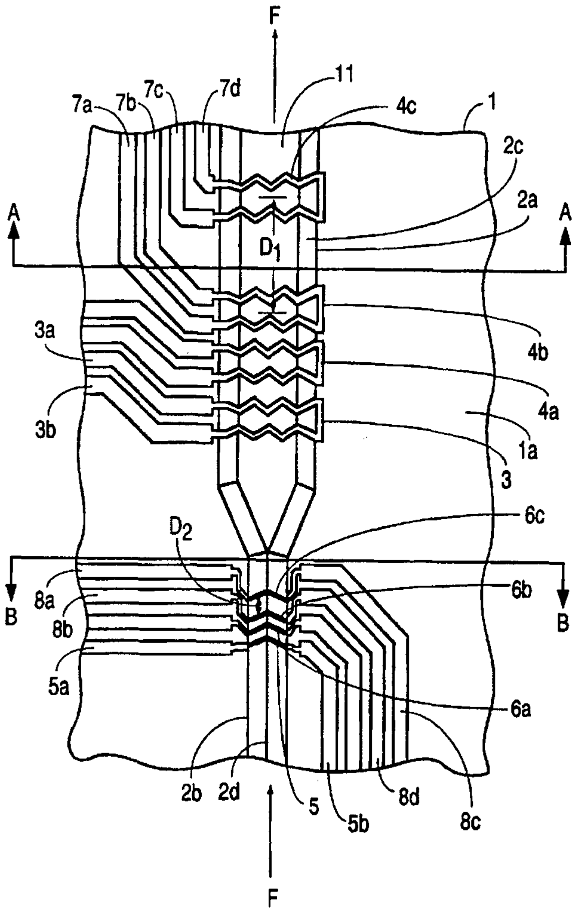
(54) Title: PULSED THERMAL FLOW SENSOR SYSTEM

(57) Abstract

A fluid flow meter fabricated by micromachining techniques measures a wide range of fluid flow rates. Two serial portions (2a, 2b) of an enclosed channel (2) have different cross-sectional areas, and therefore different flow rates. Each channel portion has its own flow sensor set (4a, 4b, 4c and 6a, 6b and 6c), which operate by using a heating element (3, 5) to inject a thermal pulse into the flow channel. The fluid carries the thermal pulse through the flow channel to two sensor elements (4a, 4b and 6a, 6b) spaced apart along the channel downstream from the heating element. The transit time of the thermal pulse between the two sensor elements measures the fluid flow velocity. The operating ranges of the two sensor sets disposed respectively in the narrow and wide channel portions (2b, 2a) overlap, providing a wide dynamic measurement range. A closed control system including the fluid flow meter and a solenoid-operated valve delivers fluid using a duty cycle approach, for applications such as intravenous drug administration.



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PULSED THERMAL FLOW SENSOR SYSTEM

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to a fluid flow meter and system for using same, and specifically to a flow meter formed by micromachining and having a channel with portions of different cross-sectional area, and including a pulsed heating element and two spaced-apart downstream heat sensors for precisely measuring fluid velocity.

Description of the Prior Art

It is known to introduce heat into a fluid stream to measure fluid flow. One such device includes two heating elements placed in the fluid stream; both elements are electrically heated and cooled by a stream of fluid. The upstream element is cooled by the fluid stream more than the downstream element, and the measured temperature difference between the two elements indicates flow.

Another method employs a heating element, a temperature sensor upstream from the heating element, and a temperature sensor downstream from the heating element. Fluid passes by the upstream sensor and is then heated by the heating element, while the heated fluid continues on to the downstream sensor. The measured temperature difference between the upstream and downstream sensors determines flow rates. Both the two and three element configurations described above have been formed using semiconductor micromachining technology.

To accurately measure flow using these techniques without calibration, the specific heat and thermal conductivity of the fluid and the various components of the flow meter must be known precisely. Moreover, the effects of thermal conductivity vary with changes in flow rate, ambient temperature, fluid temperature, fluid type, and fluid concentration. One method of compensating for thermal conduction losses includes adding another sensing element in a closed off channel to compensate the device for thermal conduction losses. In a gas application, this is relatively easy; however, in a liquid application, it is difficult to ensure this dead-end channel becomes primed.

Other thermal flow meters overcome some of the above disadvantages. One such approach (Miller, Jr. et al., U.S. Patent No. 4,532,811) applies a thermal pulse to a stream of fluid and has a single downstream heat sensor to sense the thermal pulse. The transit time between the heating element and the heat sensor determines flow velocity. The Miller thermal pulse technique is effective over a wide range of fluid temperatures, because the unheated fluid is used as a reference: the downstream sensor detects thermal pulses, i.e. envelopes of fluid traveling through the flow channel that are warmer than the unheated fluid. Therefore, the thermal pulse technique is advantageously insensitive to changes in ambient temperature.

A major disadvantage of Miller's approach is that there is a delay associated with the transfer of heat to and from the fluid. This delay is associated with the thermal masses, thermal conductivities, and heat-transfer coefficients of the heating element, sensor, and fluid, and must be accounted for when calculating flow rates. Since the delay is related to the properties of the fluid, the flow meter inconveniently must be recalibrated for different types and concentrations of fluids.

SUMMARY OF THE INVENTION

A device and method for measuring flow in accordance with the present invention provide power pulses to a heating element and thereby inject a small thermal marker (pulse or signal) into a stream of fluid (gas, liquid, or a combination thereof) traveling through an enclosed flow path of known cross-sectional area. Two or more sensors, spaced apart downstream from the heating element, detect the passage of the thermal marker. The thermal marker may be, alternatively to a pulse, a pulse superimposed on a baseline heating level, or e.g. a sinusoidal signal. The method to determine flow rate measures the time between markers. In one version this time is the peak at the first sensor to the peak at the second sensor. This is done in one embodiment electronically by differentiating the amplified signals, then using comparator circuits to find the zero-crossing points, and thereby producing a digital pulse with a length approximately equal to the time between the peaks. Alternatively, a leading edge of the marker is detected by the sensors.

A flow meter's dynamic range limits are defined by the minimum and maximum measured flow rates. At high flow velocities, fluid passes by the heating element too quickly to allow sufficient heat to transfer from the heating element to the fluid, and from the fluid to the downstream sensors. At low flow velocities, results are poor because the thermal pulse dissipates in the fluid.

To improve dynamic range, one embodiment of the present invention measures velocity in two portions of the channel, the portions having different cross-sectional areas, thereby providing different flow velocities. The narrower channel portion is used for measuring low flows, and the wide channel portion is used for measuring higher flows. This combines the dynamic ranges of the two portions, thereby substantially increasing the overall dynamic range of flow meter.

The flow sensor in one embodiment is a silicon chip made by microetching a silicon substrate and film deposition techniques. Such sensors find particular utility in a wide variety of medical applications, such as precise intravenous drug delivery.

More particularly, a heating element and the heat sensors are formed in situ on integral members bridging across or extending into a channel of the substrate. The bridging members are formed by deposition and etching, followed by etching the channel in the substrate to define the lower half of the flow path. A glass or silicon cover with a channel similar to that etched in the substrate is bonded to the substrate. The channel on the substrate and the channel on the cover are aligned to form an enclosed flow path of known cross-sectional area. The heating element and sensors are deposited on the bridging members which traverse the enclosed flow path, and so are in thermal contact with the fluid stream. In one embodiment, the bridging members approximately bisect the enclosed flow path formed by the substrate and matching cover. Also, the heating element and sensors in one embodiment are active only in the central portion (away from the sidewalls) of the channel.

An advantage of this device (unlike many prior art flow sensors) is that individual flow sensors need not be calibrated once the design has been characterized if fabrication process tolerances are precisely maintained. If the flow channel cross-sectional area and sensor spacing are maintained within a desired range (which is easily achievable using conventional semiconductor and micromachining processing techniques) then volume and flow calculations can be made to achieve a result relatively insensitive to any other parameters, including fluid properties, exact heater and sensor characteristics, or exact electronic gains or offsets. In addition, accuracy over a range of ambient and fluid temperatures is also maintained. Thus instead of measuring temperature directly, a time value determined by flow rate is measured, removing any first order calibration effects.

Fabrication by micromachining has the additional advantage of enabling manufacture of extremely small flow meters. As a result, many flow meters may be fabricated simultaneously, lowering cost per unit. Moreover, small size enables measurement of very low flow rates given precise manufacturing tolerances.

A flow meter in accordance with the invention is useful with a closed loop flow control system for delivery of intravenous drugs. In accordance with one embodiment, in this application it is possible to deliver flow rates of 0.3 ml per hour to 125 ml per hour. In the prior art, closed loop control at such low flow rates is not possible without prohibitively expensive components. The flow meter of the present invention uses relatively inexpensive and hence potentially disposable components. Such a closed loop control system, using a conventional solenoid-operated valve, delivers fluid at user selected flow rates from an intravenous bag or from a source of pressurized liquid, such as an elastomeric balloon serving as a liquid reservoir in an infuser. Delivery at low flows is by controlling the duty cycle of the valve, and integrating valve flow over time to determine volume delivered. A low flow measurement is made to compensate for leakage when the valve is nominally off.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1a shows a plan view of the surface of a device in accordance with the invention.

Fig. 1b shows a plan view of a second embodiment of a heater element or sensor.

Fig. 2 shows an exploded cross-sectional view of the wide portion of the flow path of Fig. 1a.

Fig. 3 shows an exploded cross-sectional view of the narrow portion of the substrate channel of Fig. 1a.

Fig. 4a shows the device of Fig. 1a in a closed loop flow control system.

Fig. 4b shows circuitry for use with the device of Fig. 1a.

Fig. 4c shows a plan view of a device in accordance with the invention including extra on-chip heater elements.

Figs. 5a to 5d show fabrication of the device of Fig. 1a.

DETAILED DESCRIPTION OF THE INVENTION

Fig. 1a shows a plan view drawn to scale of a portion of the surface of a silicon substrate 1 (in one embodiment measuring 2.5 mm x 5 mm at any convenient thickness) in accordance with one embodiment of the present invention. (It is to be understood that materials other than those disclosed herein may also be used). In the surface of substrate 1 is etched channel 2, having a wide portion 2a and a narrow portion 2b.

Figs. 2 and 3 show cross-sectional views of a glass or silicon cover 12 and the substrate 1 as viewed along line B-B and line A-A, respectively, in Fig. 1a. A groove (channel) 13 is etched in a surface 12a of cover 12, the groove having wide and narrow portions corresponding to the wide and narrow portions of the channel 2 of substrate 1. The cover 12 is anodically (or wafer) bonded to the substrate 1 so that the channel 13 of cover 12 aligns with the channel 2 of substrate 1 to form a flow path for fluids.

Referring again to Fig. 1a, the wide portion 2a of substrate 1 is traversed by a heating element 3 and heat sensors 4a, 4b, and 4c, which are located downstream along channel 2 with respect to the direction of flow F. Heating element 3 has a zig-zag shape because of the need for a silicon fabrication etching step to undercut the heating element 3 which is a bridge formed in substrate 1 traversing channel 2. This is because for a sensor aligned along the <110> direction with substrate 1, which is the direction that an etched V-groove (as is channel 2) forms on a {100} oriented silicon wafer, a sensor element 3 formed straight across a groove (channel) will not be undercut.

Similarly, the narrow channel portion 2b is traversed by a chevron-shaped heating element 5 and downstream heat sensors 6a, 6b, and 6c. Structurally and electrically, element 3 and associated sensors 4a, 4b, and 4c are identical, as are element 5 and associated sensors 6a, 6b, 6c.

When the cover 12 and substrate 1 are bonded, the heating elements 3, 5, and sensors 4a, 4b, 4c, 6a, 6b, 6c bisect the flow path formed between substrate 1 and glass cover 12, and are therefore in contact with the fluid stream. Traces 3a and 3b provide power to heating element 3, while traces 7a, 7b, 7c, and 7d provide a signal path for sensors 4b and 4c. In the narrow portion of the channel 2b, traces 5a and 5b provide power to heating element 5, while traces 8a, 8b, 8c, and 8d provide a signal path for sensors 6b and 6c. Traces 3a, 3b, 7a, 7b, etc. are about 5 μm wide and 3000 Å thick. Alternatively, in another embodiment any of elements 3, 4a, 4b, 4c, 5, 6a, 6b, 6c cross channel 2 only once (instead of twice as in Fig. 1) with connecting traces formed on both sides of channel 2.

To measure the flow of fluid through the wide portion of the flow path, external circuitry (described below) provides power pulses to the heating element 3 and thereby forms a small thermal marker (pulse) in the fluid stream. This thermal marker is carried downstream by the fluid where it sequentially encounters sensors 4a, 4b and 4c. The transit time T_1 of the thermal pulse between for instance downstream sensors 4b and 4c is a representative time measure of the flow velocity of the fluid inside the enclosed flow path. (It has been found experimentally that at flow rates of 2 to 20 mL/hour that the relationship between indicated velocity and flow rate is not linear or accurately predictable without calibration of a particular design. This is because the sense elements slow down the flow in their vicinity.) Because the cross-sectional area A_1 of the wide portion of the enclosed path is known, as is the distance D_1 between sensors 4b and 4c, the volume V_1 between downstream sensors 4b and 4c is easily determined. ($V_1 = A_1 \times D_1$). Flow F, in volume per unit time, is approximated by dividing the volume V_1 by the transit time T_1 ($F = V_1 \div T_1$) and is normally expressed in cubic centimeters per hour (cc/hr).

Thus, because volume V_1 and spacing D_1 are precisely known, nominal flow F may be calculated regardless of the exact thermal conductivity, density, or concentration of the fluid. Because the cross-sectional area A_2 of the narrow portion of the flow path and the distance D_2 between sensors 6b and 6c are also precisely known, nominal flow F may likewise be calculated in the narrow portion of the flow path. Under conditions of very low flow, the thermal pulse may dissipate before it reaches the far downstream sensor. Under these flow conditions, the difference in transit time between the two flow sensors obviously cannot be measured. The dynamic range of the device can be increased, therefore, if for very low flows the transit time from the heater to the first downstream sensor can be measured, with the appropriate calibration factors.

In one embodiment of the present invention, the spacing D_1 between sensors 4b and 4c is 325μm from center to center. The same spacing is used between heater element 3 and sensor 4b. The spacing is generally not a critical dimension. It is preferred to operate the device with a very low Reynolds number. For a cylindrical tubeshaped channel, it is well known that the flow is zero at the walls, and the average velocity is exactly half of peak velocity; the same is true across the height of a wide rectangular channel. The sensors tend to average the flow velocity to which they are exposed. That is, the very center of each sensor such as 4b, 4c will observe the heat pulse before the outside part of the sensor does so.

Thus depending on the exact heater and sensor geometry, the transit time as measured by the thermal pulse will be intermediate between the average fluid transit time and the peak fluid transit time. This relationship must be determined for any particular sensor geometry, and a single factor can be introduced to more accurately relate the measured cross sectional area and thermal transit time to the fluid flow. Since the parabolic flow profile holds over the entire range of laminar flow, this factor does not need to be adjusted over the operating flow range of the device.

In another embodiment, each heater and sensor element is active only in the center of the channel. This measures flow closer to the peak rather than the average. Such structures for instance extend the sensor/heater trace metallization partway across the channel. This embodiment of the heater and/or sensor elements is shown in Fig. 1b, showing in plan view (as in Fig. 1a) a single e.g. heater element 4d which is supported on a support structure 10 suspended over flow channel 11. Low resistance connections (traces) 7e, 7f connect to serpentine heater (or sensor) element 4d. By having the heater and/or sensors active only in the central portion of the flow channel (such as the central 1/3 thereof) one achieves more accurate flow detection by reducing flow effects at the flow channel walls.

In one embodiment, the flat bottom 11 (see Figure 2) of the wide portion of the channel 2 is 220μm wide and etched 80μm into the substrate 1. The width of channel 2 at the surface 1a is 300μm. The channel 2 cross-sectional area, taking into account the angled sides 2c of channel 2 but ignoring the heating and sensing elements is 23.4×10^3 μm^2. The glass cover (cap) 12 is isotropically etched, so its etched profile is not exactly symmetric with the substrate groove 2 which is anisotropically etched. The wide portion of the channel 13a is etched 88μm deep. The resulting cross-sectional area is approximately equal to that of the wide channel 2a of the substrate 1. Thus, the cross-sectional area of the wide portion of the flow path is approximately twice the cross-sectional area of the wide portion of the channel 2a of substrate 1, or 46.8×10^3 μm^2, and the volume V_1 of the portion of the flow path between sensors 4b and 4c is the cross-sectional area A_1 times the distance D_1 between sensors 4b and 4c, or 15.2×10^6 μm^3. Dividing the constant V_1 by the transit time T_1 of the thermal pulse between sensors 4b and 4c results in the flow rate F in volume per unit time.

Similarly, the flow of fluid in the narrow portion 2b of channel 2 may be accurately calculated as the cross-sectional area A_2 of the narrow portion of the flow path multiplied by the distance D_2 between sensors 6b and 6c, and divided by the transit time T_2 of the thermal pulse as it travels between sensors 6b and 6c. In one embodiment, the sensor spacing D_2 between sensors 6b and 6c is 70μm, the cross-sectional area A_2 of the narrow portion of the flow path is 7.0×10^3 μm^2, and the volume V_2 is 4.9×10^5 μm^3.

Given the relatively small cross-sectional areas of both the wide and narrow regions of the flow path, the power required to provide the necessary thermal pulse in the fluid stream is quite low. In the wide portion, heating element 3 is provided a 700μs duration, 2.6V pulse. The nominal resistance of heating element 3 is 75Ω, so the resulting average power over one duty cycle is approximately 45mW. In the narrow portion, heating element 5 receives a rectangular voltage pulse of about 2V amplitude and 300 μsec duration. The nominal resistance of heating element 5 is 27Ω, so the resulting average power over one duty cycle is approximately 72mW.

The exact heater pulse amplitude, frequency, and duration may be varied; measurements of gas flow require less power than does liquid flow. Generally, a pulse of shorter duration than a characteristic time associated with the heat capacity and thermal diffusivity of a volume of water surrounding the sensor (for liquid flow) is appropriate. That is, short high amplitude pulses are most effective. Pulses which are short compared to the minimum delay time associated with the maximum flow velocity and the sensor spacing are also preferred. The pulse repetition rate is only limited by the delay time for the lowest flows; typically repetition rates of the power pulses up to about 100 Hz are used with the device of Fig. 1a. If the flow is known to be changing slowly, the repetition rate can be reduced, as would be desirable in a battery powered system.

The dynamic range is defined by the minimum and maximum measurable flow rates and in one embodiment is about 400:1. For very low flow rates, as low as 0.3 cc/hr in one embodiment, the flow sensor measures the higher fluid velocity V_2 in the narrow portion of the flow path. For higher flow rates, as high as 300 cc/hr in one embodiment, the flow sensor measures the lower fluid velocity V_1 in the wide portion of the flow path. It is to be understood that this wide/narrow approach is applicable to fluid flow measurement techniques generally, and is not restricted to pulsed heating or the use of two sensors. At very high flow rates for a given sensor the heat pulse amplitude decreases due to the heat pulse passing the sensor in a very short time, while at very low flow rates the heat pulse diffuses away to the channel walls before it can reach the downstream sensors. These limits are set for both stages (channel widths) of a dual stage device as shown in Fig. 1a, and an appropriate cross-over flow rate set between the use of the two stages.

The flow sensor of Fig. 1a is typically used in a closed loop flow control system as in Fig. 4a for instance for infusion of drugs where the flow rate is to be controlled, i.e. intravenous drug administration. Fluid reservoir 14 holds the fluid to be delivered to tubing 15. Inserted in tubing 15 is a conventional on/off solenoid valve 16 controlled by controller 17, described below. Flow sensor 18 is also installed in tubing 15 and provides data as to the measured flow rate to controller 17. Downstream of sensor 18 the fluid is provided, for instance by a conventional intravenous needle, to the patient. It is to be understood that such closed loop control systems for flow control are well known.

In use, the controller 17 first determines that valve 16 is off by checking for leaks (i.e., flow detected by sensor 18). Thus when valve 16 is off it is determined if there is any flow through sensor 18. If there is a flow, i.e. a leak is present, the leak rate is computed by controller 17 from the data provided by sensor 18. Then this leak measurement is used to correct later flow calculations. Then, the presence or absence of a leak having been determined, valve 16 is opened by controller 17 and the presence of flow is checked by sensor 18, i.e. whether valve 16 has indeed opened, by means of sensor 18 measuring the flow rate. It is generally assumed that the flow rate is constant. Controller 17 computes how long valve 16 must be open to deliver a needed volume of fluid as determined by user input from keypad 19, conventionally operably connected to controller 17. Data as to the user input information and the measured flow rate is displayed by conventional LCD display 20, also conventionally associated with controller 17. Controller 17 includes a conventional 4-bit microprocessor having a resident control program for performing the control functions as described herein. Controller 17 also includes a conventional LCD controller for controlling the data displayed on LCD display 20.

Typically controller 17 operates valve 16 to be open for a brief period periodically (such as every two minutes) to deliver the desired amount of fluid as programmed into controller 17 via keypad 19. Thus controller 17 calculates the average required flow rate depending on the input fluid volume needed. The flow rate is measured by sensor 18 while the actual delivery of the fluid is provided by operation of valve 16. Sensor 18 measures the flow continuously, in one embodiment taking approximately 10 flow rate measurements per second. By integrating the flow rate over time it is possible to determine flow fluctuations, i.e. if the flow rate is not constant.

Controller 17 includes analog electronic circuitry for analyzing the data from sensor 18. (The conventional power source for the heater elements is not shown). The analog electronic circuitry includes a constant current source 20, amplification stage 22, differentiating stage 24, a comparison stage 26, and a latch stage 28 (see Fig. 4b).

The constant current stage 20 measures the changes in resistivity. When a constant current from current source 21 is applied across a resistor (the sensor elements), any change in resistivity causes a comparable change in voltage across the resistor (as determined by Ohms law). By using constant current source 21, the change in resistivity of each sensor element (not shown but connected to terminals 30) is tracked by the change in voltage. The constant current source 21 will heat the fluid via the connected sense resistor in the same fashion as it heats the heater element. It is therefore preferred to keep the power applied to the sense resistor much lower than that applied to the heater pulse.

Because of the low power requirement noted above, the signal from the sense element resistor in the flow sensor is very small. An amplification stage 22 including amplifiers 23, 32 raises the signal to usable levels. Also at this point, the signal is AC coupled in this embodiment to the amplifier 32 to allow for changes in ambient temperature.

At this point in the circuit, the signal is a voltage proportional to fast changes in the resistance of the sense resistor. It is needed to find the peak resistance of the sense resistor. Therefore, the signal is differentiated by differentiating amplifier stage 24 including amplifier 36. When the signal is differentiated, the output is directly related to the slope of the original waveform. When the peak resistance is reached, the output signal of an amplifier 36 changes sign from negative to positive. Although this negative-to-positive transition occurs during the peak resistivity, it can also occur when no signal is applied to the system whatsoever. This shows up as noise on the output and must be accounted for as described below.

A comparator 38 in comparison stage 26 detects the sense resistor's peak. Comparator 38 is used in conjunction with the differentiating amplifier 36. The output signal of the comparator 38 goes high when the differentiator 36 crosses through the zero, thus corresponding to the peak resistivity.

This alone is not enough to filter out the slope changes when no signal is present. To do this, a second comparator 40 determines when a signal is present. Although the signal is AC coupled to the amplifier stage 22, the time constant of the AC coupling is much greater than the signal length; therefore, the system works in a DC coupled environment during the duration of the sample. Thus a maximum noise threshold is determined for the signal. Any signal with more amplitude occurs only during a sample period. During this period, the zero point crossing out of the differentiator 24 is the crossing of interest. By connecting an input terminal of comparator 40 to the output terminal of the amplifying stage 22, and second input terminal of comparator 40 to a voltage source, which supplies a small voltage greater than the maximum noise value, an active region of interest is obtained at the output of comparator 40. Logically ORing in latch stage 28 the output signals of the two comparators 38, 40 together, a pulse with the leading edge corresponding to the peak resistivity of the sensor is obtained, without any spurious edges.

By using a second set of similar current 50, amplification 52, differentiating 54, and comparison 56 stages for the second of the two sense resistors, two pulses are obtained. The first pulse corresponds to the voltage across the first sense resistor, and the second pulse corresponds to the voltage across the second sense resistor. Using two latches 28, 58, the first signal latches a flip-flop 62 active high. The second pulse resets the first flip-flop 62 returning it to a low state. The output waveform at terminals 66 is the same as the time of flight between the two sense resistors.

The above-described electronics senses a change in resistance of the sensor elements by using a constant current source to maintain a low level current through the sensor, then observes changes in the voltage drop across the sensor elements. An alternative method provides a bridge connected to each sense element. The output signal of the bridge converts the change in resistance in the associated sensor element into a small voltage which is then amplified. Advantageously this bridge can be easily adjusted to accommodate the part-to-part variations in nominal resistance. Also, the output signal of the bridge corrects for changes in ambient temperature. Since the bridge includes only passive components, it reduces noise introduced into the output signal.

In a system as shown in Fig. 4a, a pulse of voltage provided to the heater element while an air bubble is passing by the heater element can cause the heater element to burn out due to insufficient heat dissipation by the air bubble, compared to the fluid normally present. One solution to this problem is to provide an additional heater element (see Fig. 4c) located on the silicon portion of sensor 18 but not in contact with the flow channel. This additional heater element is electrically identical to the heater associated element in the flow channel. The two heater elements are connected as portions of the conventional null-seeking bridge circuit so the heater element in the flow channel is raised to a particular temperature, which is set by the other resistance values in the bridge.

This additional heater element also allows, in addition to preventing heater burnout, detection of the presence of bubbles in the sensor. These bubbles would typically confuse the flow measurements by sensor 18. The detection of the presence of a bubble thus would indicate to controller 17 not to report the measured flow at that time.

The additional heater element also allows driving of the heater element in the flow channel so as to maintain a controlled temperature, rather than the above-described method of providing a specified voltage for a predetermined time. In this controlled temperature mode, the amplitude or duration of the power pulse is adjusted using signal amplitude feedback to provide uniform signal strength.

The above described circuitry of Fig. 4b includes AC coupling of the signal to the amplifier stage 22. The amplifier alternatively is one of four basic types, although some types are better suited for this application. The four types are:

	Single-ended Input	Differential Input
AC Coupled:	Single/AC	Differential/AC
DC Coupled:	Single/DC	Differential/DC

Single-ended inputs have the disadvantage of not rejecting common mode noise very well. An AC coupled amplifier (as described above) is not subject to slow drift of the signal caused by changes in ambient temperature.

The differential/DC type amplifier gives good signal fidelity and freedom from noise. By itself, it is susceptible to the drift of the signal already mentioned. A method of dealing with this drift is to add a baseline restoration circuit. This circuit is activated by the logic signal which starts the heater pulse. In the 150 μsec that follow, a null-seeking amplifier pulls the baseline to zero by adjusting the bias on the first amplification stage. The circuit is then de-activated. In typical operation, the rising edge of the thermal marker appears on the output from the first sensor 180 μsec or more after the start of the heater pulse. Thus, the baseline adjustment is over before the signal from the thermal marker arrives.

Fig. 4c shows a device as in Fig. 1a with the addition of on-chip additional heater elements 70a, 70b associated with sensors 4b, 4c and additional heater elements 72a, 72b associated with sensors 6b, 6c. Also shown are bonding pads 74-1, ..., 74-k and liquid feedthrough holes 76a, 76b. The other elements are as in Fig. 1. The direction of flow is from top to bottom of Fig. 4c.

While different in origin, the effects of variations in ambient temperature and of part-to-part differences in nominal resistance are similar. The baseline of the signal will not always be the same. An alternate design for the sensor chip and its package addresses both of these issues, by providing for instance three or four additional sensor elements identical to those used for sensing the thermal marker. One or two of these additional sensor elements may be in the flow channel, upstream of the heater element. The other two may be on the silicon substrate. These elements are connected to their respective sense elements to form half bridges. In this way, drift due to ambient temperature changes is eliminated. The rest of the bridge is on the ceramic substrate on which the chip is mounted, in the form of laser trimmed resistors. These resistors are adjusted at the time of assembly, so that all flow sensor packages are electrically and thermally identical.

Another method of measuring rate of flow, using the above described chip but a different measurement approach, is the well known first moment method of flow rate sensing, which requires integrating the sensor output over time. Such methods are already known for use in other types of flow sensors. Another method, which might work best if used with heater control feedback to produce constant amplitude signals as described above, is to pick a level on the rising edge of the signals, and use it as a time marker.

A typical fabrication sequence for a flow channel as disclosed herein, with bridging members supporting resistive heating and sensing elements, is disclosed in Renken, et al., U.S. Patent No. 4,542,650, incorporated herein by reference. Figs. 5a to 5d show cross sections through line 5-5 in Fig. 4c illustrating fabrication of the structure of Fig. 4c. (It is understood that only one die of many on one wafer is shown here.) Beginning with silicon substrate 80, which is 400 μm thick and doped to a level of 1 Ω-cm with N-type dopant, a shallow depression 82, about 8000 Å deep and 20 μm wide is conventionally etched using a mask, to recess the later-formed metal traces. Then a layer of PECVD (plasma enhanced chemical vapor deposited) oxynitride 83 is deposited to a thickness of 1 μm over the principal surface of substrate 80 to serve as bottom insulation and support for the suspended metal traces that are the heaters and sensors.

In Fig. 5a, layer 84 of platinum is conventionally deposited to a thickness of 3000 Å and patterned to serve as the heating resistors and sensors. Then in Fig. 5b a layer 86 of gold is conventionally deposited to a thickness of 5000 Å and patterned to serve as the lower resistance connections and for bonding pads. The thickness of the layer of gold is controlled to just reach the surrounding top thickness of layer 83. This insures a liquid tight seal from the fluid channel to the bonding pad region at the conclusion of the process. Then a second layer 88 of PECVD oxynitride is deposited to a thickness of 1 μm as a top passivation layer and support for the metal traces including metal layers 84, 86. Thus the metal sensor layers 84, 86 are enclosed by two oxynitride layers 83, 88 which insulate the metal layers 84, 86 from the flowing fluids (not shown). The platinum layer 84 and gold layer 86 are formed over a planar surface of substrate 80 to minimize steps which undesirably tend to cause breaks in subsequent passivation layer 88.

Then in Fig. 5c a silicon etch mask is conventionally formed and patterned to define the channel, suspended sensor and heater bridges. In the subsequent conventional anisotropic etch step these structures are formed including bridge 90 and channel 92.

Then in Fig. 5d substrate 80 is anodically bonded to Corning type 7740 glass cap 100, in which mating flow channel 96 has already been isotropically etched. Then the substrate 80 is conventionally sawn through at 102 into multiple die to expose bonding pads 94.

In other embodiments, the channel and sensors and other materials may have other dimensions and fluid flow measurement techniques other than pulsed heating may be used. Also, the entire flow sensor may be made of glass with nitride supports for the heating element(s) and sensors. The entire sensor may be made of silicon using a silicon cap; this would result in a more precise cross-sectional area and hence a more precise device. In another embodiment, instead of one channel, the chip includes multiple (such as five) parallel channels having a common input and outlet, to divide the flow.

If the spacing between heater and sensor elements in a given section is chosen to be the same and the electrical resistance of those elements is similar, the heater and sensor elements can be switched electronically, such that the downstream sensor becomes the heater and the heater becomes the downstream sensor. In this manner bidirectional flow can be measured by alternatively measuring flow in both directions in the channel.

This disclosure is illustrative and not limiting; further modifications will be apparent to one skilled in the art in the light of this disclosure and are intended to fall within the scope of the appended claims.

CLAIMS

What is claimed is:

1. An apparatus for measuring fluid flow comprising:

a body defining a conduit for flow of a fluid;

at least one element for heating said fluid and being in thermal contact with said conduit;

at least two spaced apart sensors positioned downstream of said element with respect to a direction of the flow for sensing a temperature of said fluid.

2. The apparatus of Claim 1, wherein said body comprises:

a substrate having a first surface;

a first channel defined in said first surface;

a cover having a second surface; and

a second channel defined in said second surface;

wherein said first surface is bonded to said second surface, said first channel being aligned with said second channel so as to form said conduit.

3. The apparatus of Claim 2, wherein said one element is a resistive heating element formed on said substrate and traversing a portion of the length of said first channel, said resistive heating element having a heat emitting surface exposed to said fluid.

4. The apparatus of Claim 2, wherein said sensors are formed on said substrate, each of said sensors traversing a separate portion of a length of said first channel, said sensors having a heat sensitive surface exposed to said fluid.

5. The apparatus of Claim 1, wherein said two spaced apart sensors are spaced apart less than about 500 μm.

6. The apparatus of Claim 1, further comprising circuitry for providing said element with a power pulse.

7. The apparatus of Claim 2, further comprising:

at least one additional sensor element located on said first surface and not in thermal contact with the first or second channel; and

conductors for electrically connecting said one additional sensor element to one of said two spaced apart sensors.

8. The apparatus of Claim 1, wherein said element for heating and said sensors are spaced apart from walls of said conduit.

9. An apparatus for measuring fluid flow comprising:

a body defining a conduit for flow of a fluid;

at least one element for heating said fluid and being in thermal contact with said conduit; and

at least one sensor positioned downstream of said one element with respect to a direction of the flow for sensing a temperature of said fluid;

wherein said one element and said one sensor are each suspended in said conduit and spaced apart from sidewalls of said conduit.

10. A method of measuring a fluid flow rate through a conduit comprising the steps of:

introducing a heat pulse into the fluid at a first location along said conduit;

measuring a temperature of said fluid at a second location along said conduit downstream of said first location and observing a first time when a first temperature is attained;

measuring a temperature of said fluid at a third location along said conduit downstream by a particular distance from said second location and observing a second time when a second temperature is attained; and

determining the fluid flow rate as a function of the first and second observed times and said particular distance.

11. The method of Claim 10, further comprising the steps of:

measuring an abrupt decrease in heat dissipation at said first location; and

in response, reducing an amount of power used to provide heat at said first location.

12. The method of Claim 10, wherein said particular distance is less than about 500 μm.

13. A method of sensing passage of a bubble in a flow of liquid through a conduit, using a heater element heated by electric power to introduce heat into the liquid at a first location along said conduit and a sensor element to measure a temperature of the liquid at a second location along said conduit downstream of said first location, the method comprising the steps of:

measuring an abrupt decrease in heat dissipation at said heater element; and

in response to the measuring of said abrupt decrease, decreasing a supply of said electric power to said heater element, thereby preventing overheating of said heater element.

14. An apparatus for measuring fluid flow comprising:

a body defining a conduit for flow of a fluid, said conduit having at least two longitudinal portions of different cross-sectional area, said portions thereby providing different local flow velocities; and

sensors formed in said body and in communication with said conduit for detecting a velocity of the local flow in each of said portions.

15. The apparatus of Claim 14, wherein a cross-sectional area of one of said portions is less than about $50 \times 10^3\ \mu m^2$.

16. A method of measuring a fluid flow rate through a conduit comprising the steps of:

providing a first portion of said conduit narrower than a second portion;

sensing a fluid flow rate in said first portion;

sensing a fluid flow rate in said second portion; and

for a high sensed fluid flow rate, reporting the sensed rate in said second portion, and for a low sensed fluid flow rate, reporting the sensed rate in said first portion.

17. The method of Claim 16, wherein said first portion has a cross-sectional area less than about 50% of a cross-sectional area of said second portion.

18. A system for intravenous fluid delivery comprising:

a reservoir for holding a fluid;

a valve for controlling flow of said fluid from said reservoir;

a time of flight flow meter for measuring a flow rate of said fluid from said valve;

a controller responsive to said flow meter for controlling said valve; and

tubing for connecting said reservoir to an intravenous needle.

19. The apparatus of Claim 18, wherein said valve provides a rate of flow of less than about 10 mL/hour.

20. The apparatus of Claim 18, wherein said valve provides a flow rate exceeding 250 mL/hour.

21. The apparatus of Claim 18, wherein said controller includes:

a constant current source for supplying a constant current to a sensor element in the meter;

an amplifier for amplifying any changes in voltage in said sensor element;

a differentiator for differentiating the amplified changes in voltage;

a comparator for comparing the differentiated changes in voltage to a reference voltage; and

a latch for storing an output signal from said comparator.

22. A method for low volume fluid delivery, comprising:

providing a reservoir of fluid;

controlling outflow of said fluid from said reservoir using a valve;

measuring flow rates through said valve of less than about 1.0 mL/hour; and

operating said valve in response to the measured flow rates.

23. The method of Claim 22, further comprising:
measuring a flow rate through said valve when said valve is in an off position.

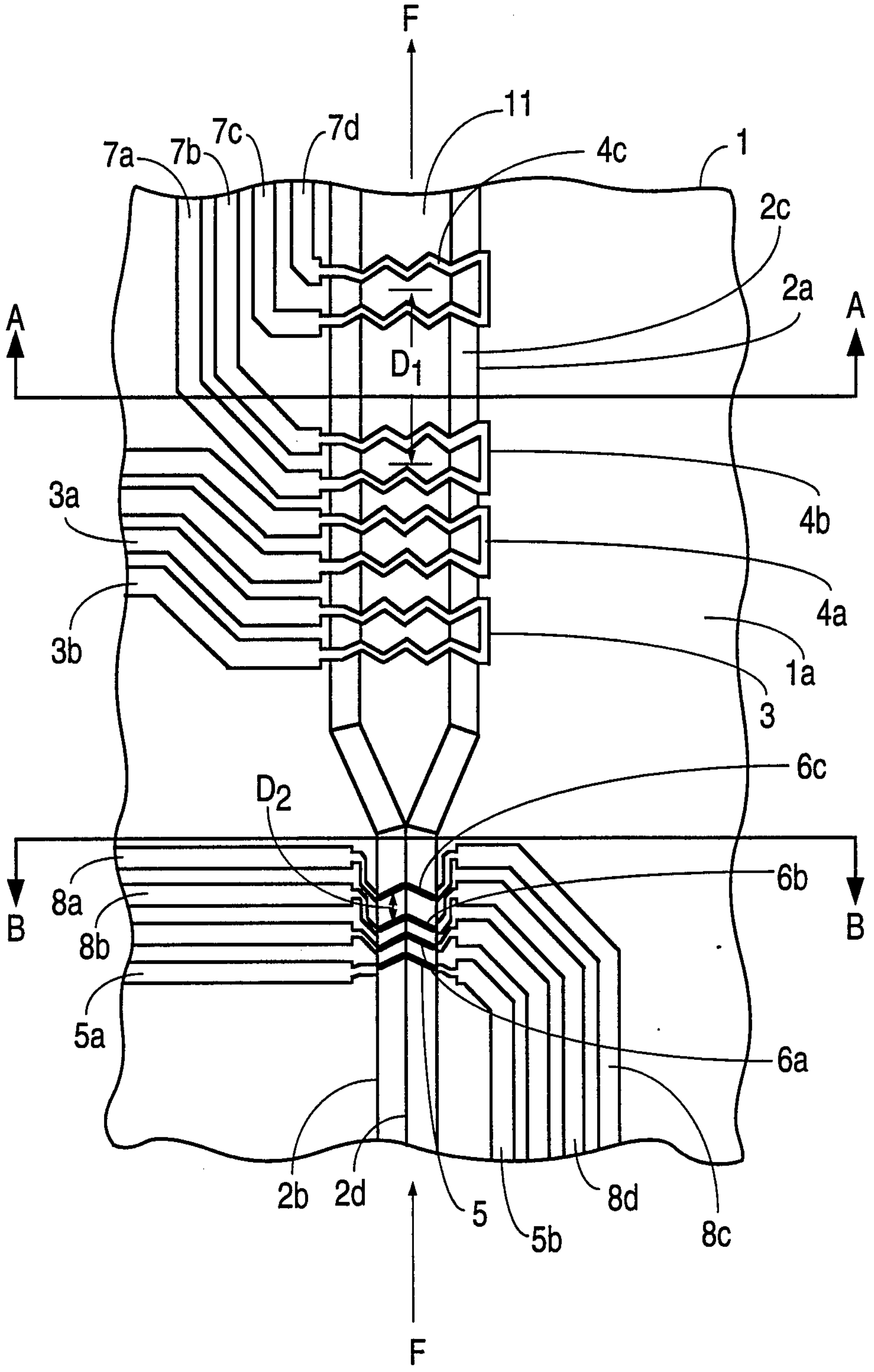

F
11
7a
7b
7c
7d
4c
1
2c
2a
A
A
D1
3a
4b
4a
3b
1a
3
6c
D2
6b
8a
B
B
8b
5a
6a
2b
2d
5
5b
8d
8c
F

FIG. 1a

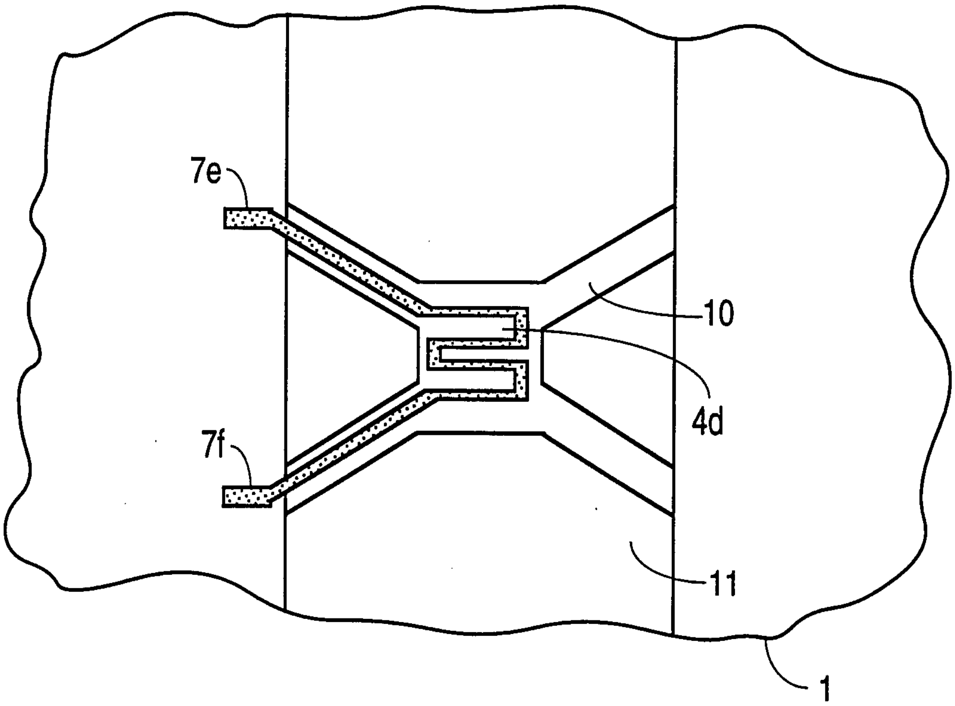


FIG. 1b

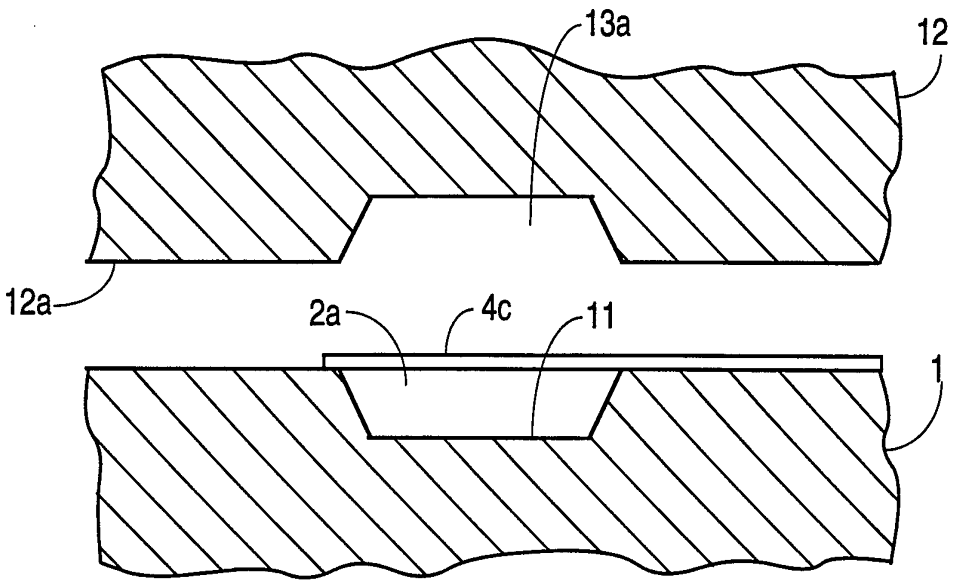


FIG. 2

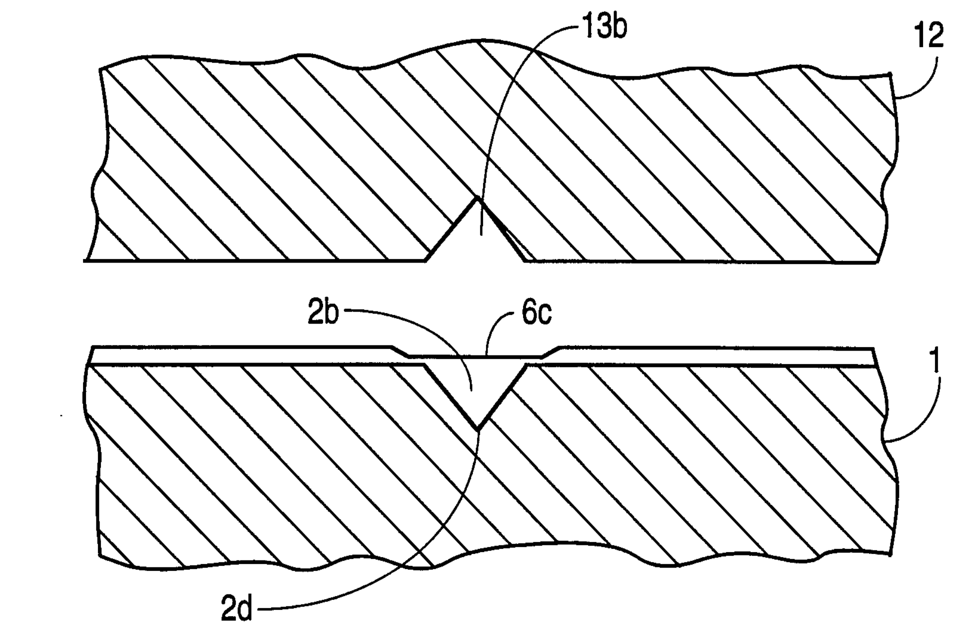


FIG. 3

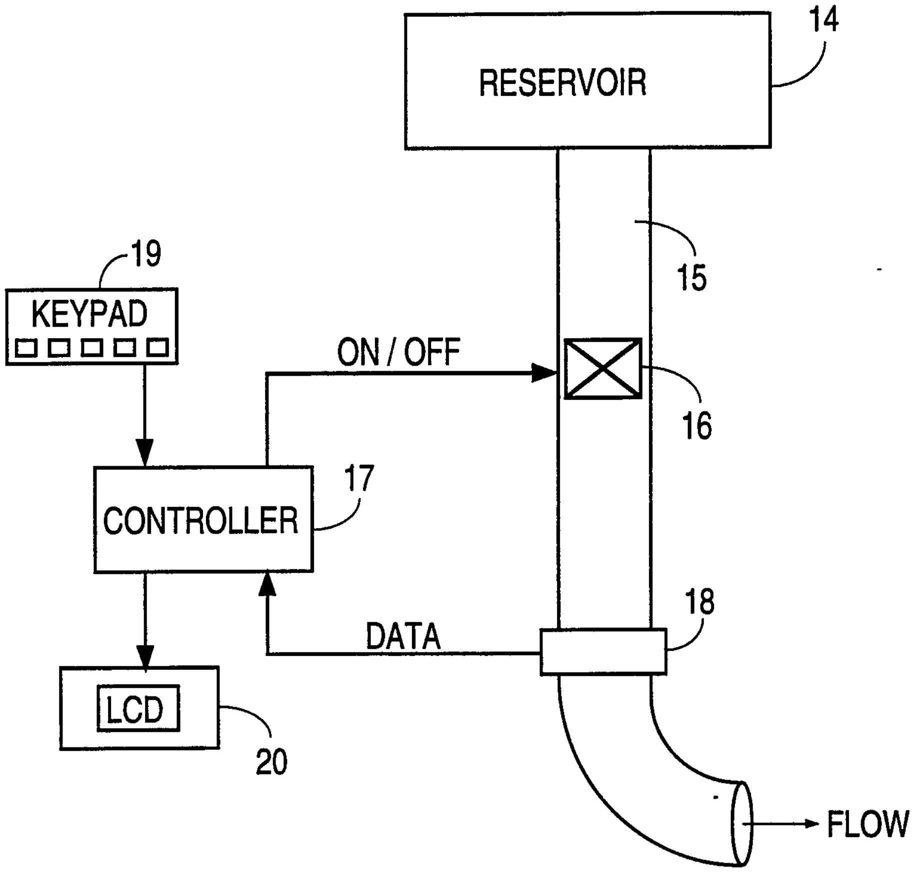
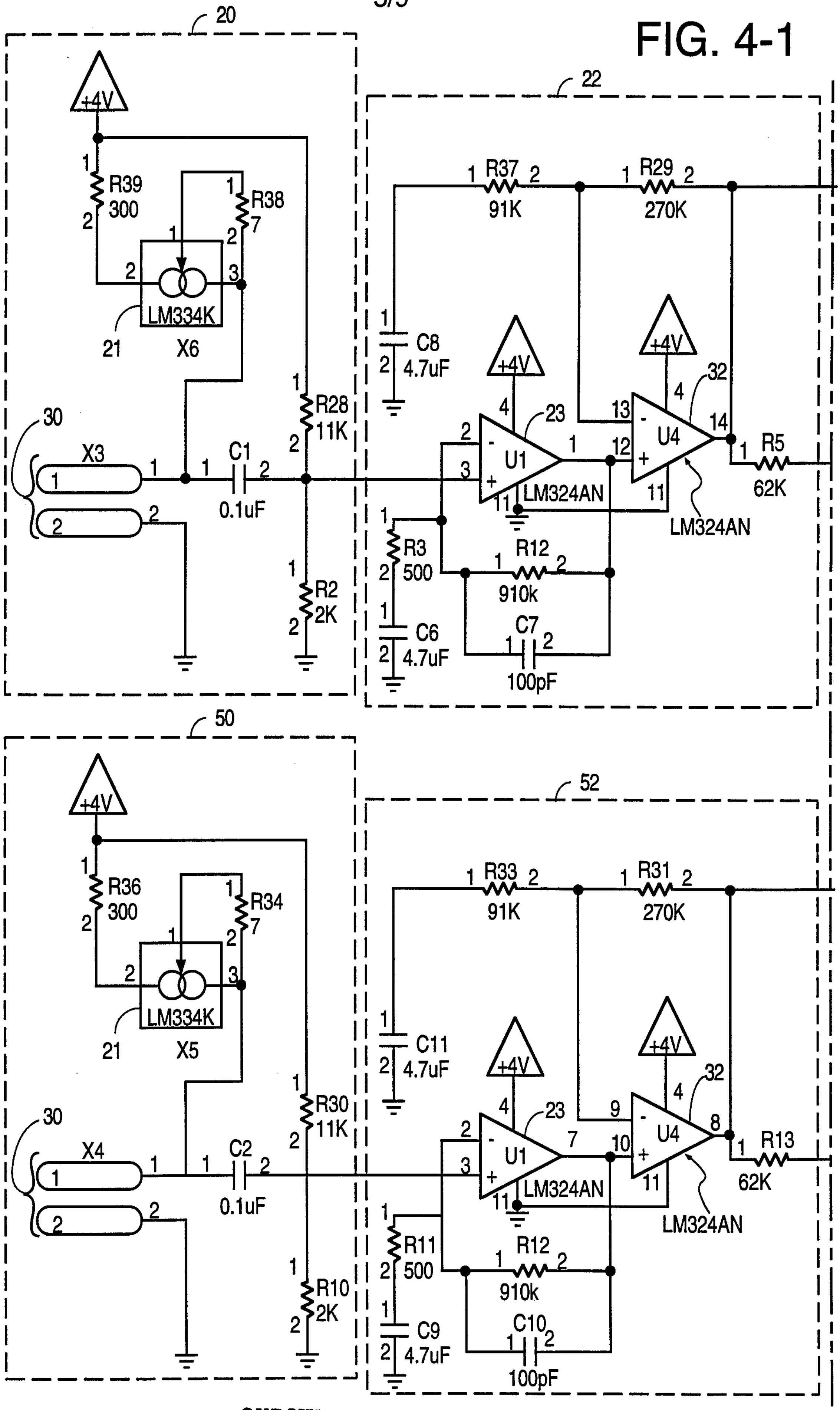

RESERVOIR
14
15
19
KEYPAD
ON / OFF
16
CONTROLLER
17
18
DATA
LCD
20
FLOW

FIG. 4a

FIG. 4-1


20
22
+4V
R39
300
R38
7
LM334K
21
X6
R37
91K
R29
270K
C8
4.7uF
+4V
+4V
32
23
30
X3
C1
0.1uF
R28
11K
U1
U4
LM324AN
R5
62K
LM324AN
R3
500
R12
910k
R2
2K
C6
4.7uF
C7
100pF
50
52
+4V
R36
300
R34
7
LM334K
21
X5
R33
91K
R31
270K
C11
4.7uF
+4V
+4V
32
23
30
X4
C2
0.1uF
R30
11K
U1
U4
LM324AN
R13
62K
LM324AN
R11
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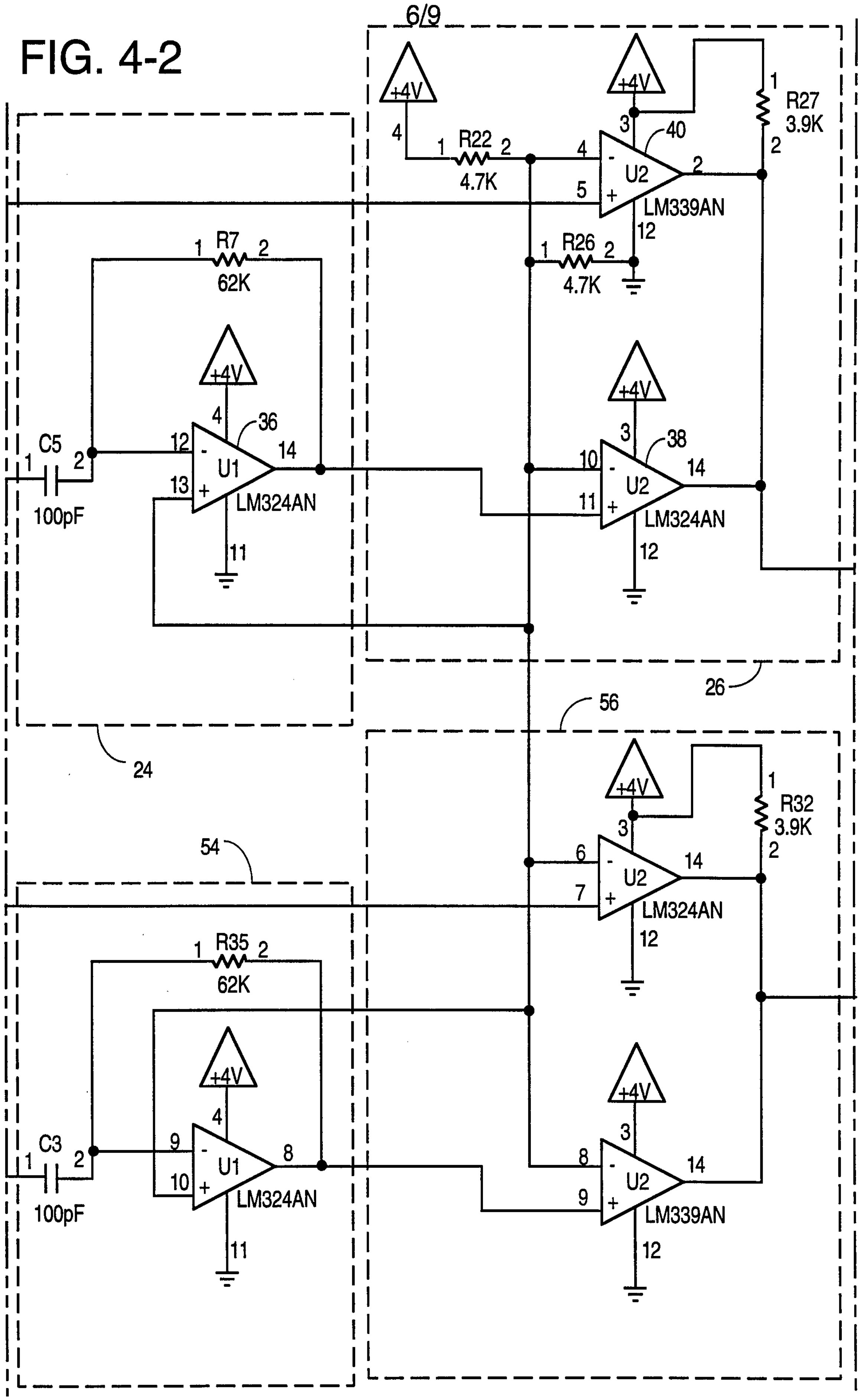
R12
910k
R10
2K
C9
4.7uF
C10
100pF

FIG. 4-2



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4
1
R22
2
4.7K
+4V
3
40
4
-
U2
2
5
+
LM339AN
12
1
R27
3.9K
2
1
R26
2
4.7K
1
R7
2
62K
+4V
4
36
C5
1
2
12
-
U1
14
13
+
LM324AN
100pF
11
+4V
3
38
10
-
U2
14
11
+
LM324AN
12
26
56
24
+4V
3
1
R32
3.9K
2
6
-
U2
14
7
+
LM324AN
12
54
1
R35
2
62K
+4V
4
C3
1
2
9
-
U1
8
10
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LM324AN
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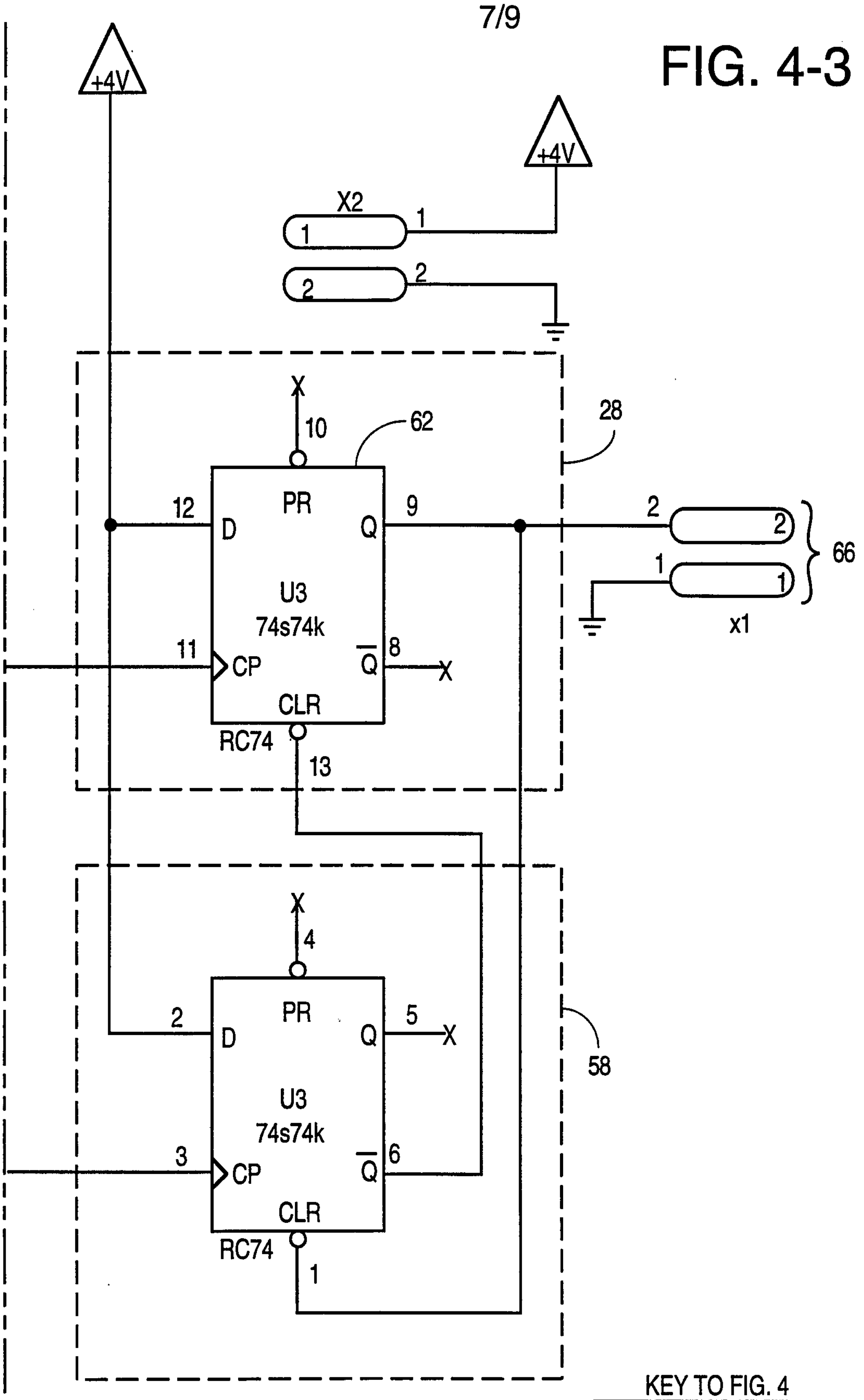
3
8
-
U2
14
9
+
LM339AN
12

FIG. 4-3



KEY TO FIG. 4

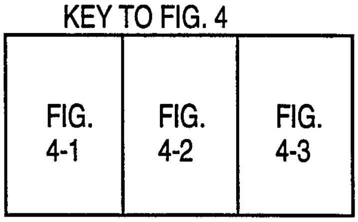


FIG. 4

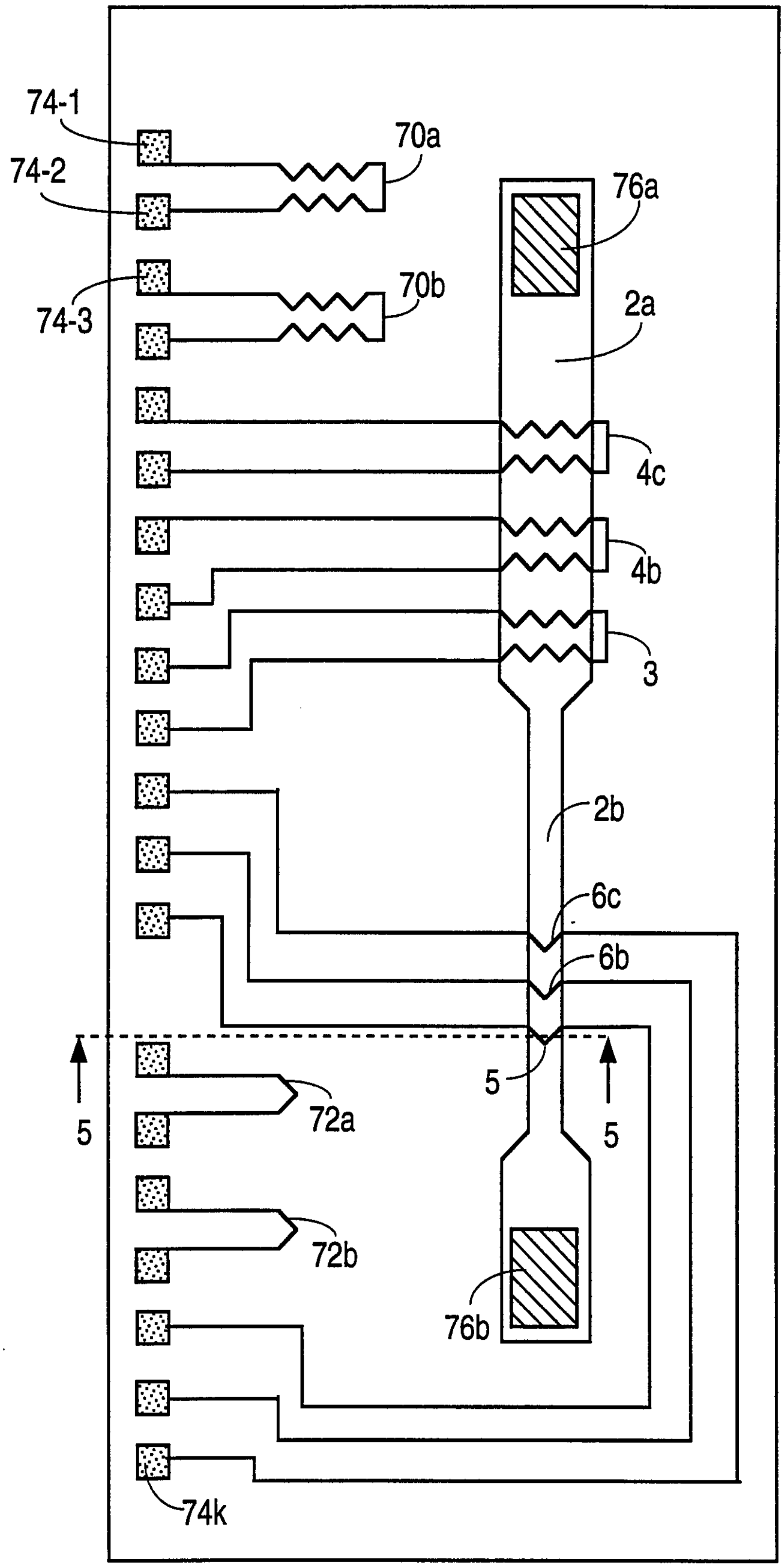


FIG. 4c

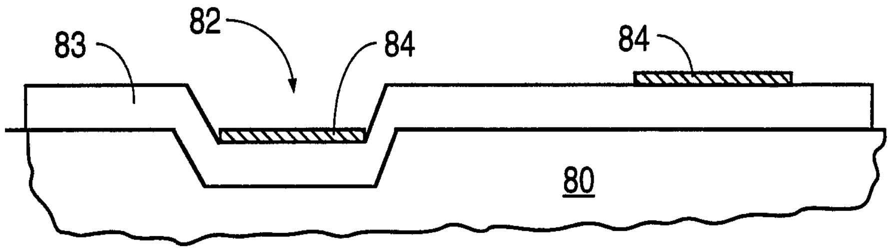


FIG. 5a

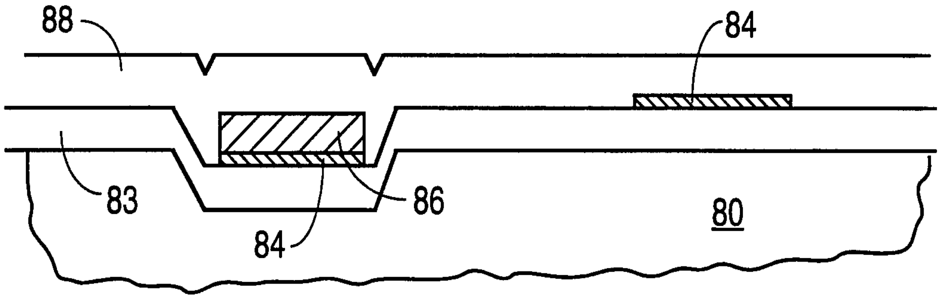


FIG. 5b

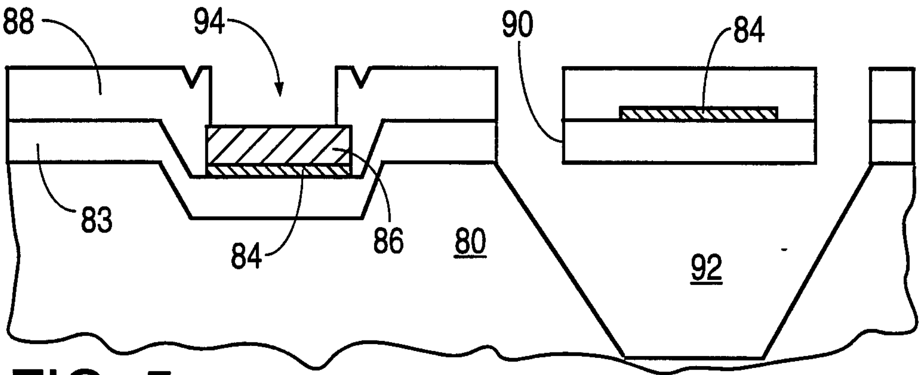


FIG. 5c

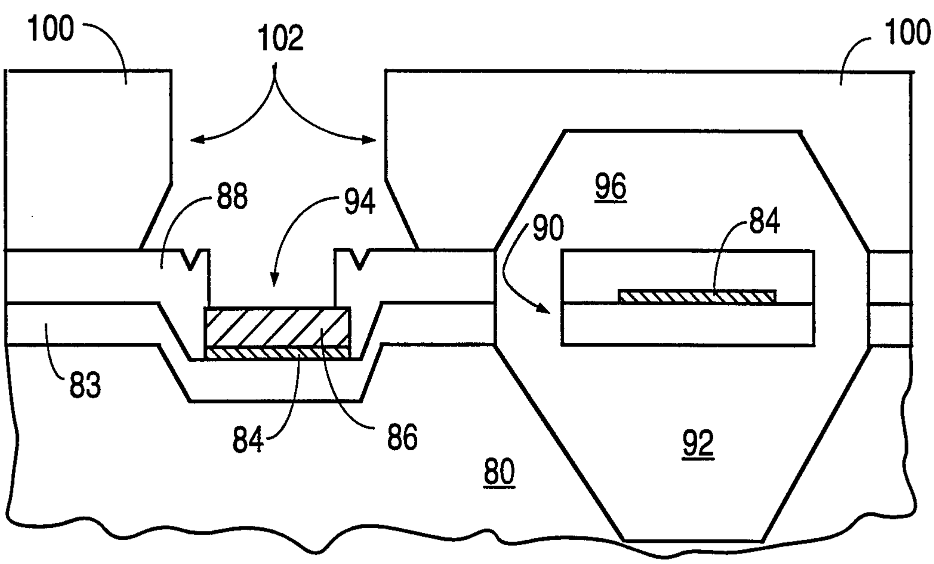


FIG. 5d

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US94/07392

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :Please See Extra Sheet.
US CL :73/ 195, 861.95; 137/459; 340/632; 604/65
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 73/ 19.01,195, 204.26, 861.95; 137/459; 340/603, 632; 604/65, 67

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

none

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

none

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X ---- Y	US, A, 4,502,339 (HORN) 05 MARCH 1985, See Fig.3	1,6,8,9 and 10 ---------------- 2-4,5,7 and 12
X ---- Y	US, A, 4,237,730 (FENG) 09 DECEMBER 1980, see Fig.1	1,6,8,9 and 10 ---------------- 2-4,5,7 and 12

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be part of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 OCTOBER 1994	14 NOV 1994
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	Authorized officer HERBERT GOLDSTEIN
Facsimile No. (703) 305-3230	Telephone No. (703) 305-4930

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X ---- Y	DE, A, 2,934,565 (MAGORI) 19 MARCH 1981, See Fig.1	1,6,8,9 and 10 --------- 2-4,5,7 and 12
Y	US, A, 4,813,280 (MILLER JR. ET AL) 21 March 1989, see element 16 Fig.3	7
A	US, A, 4,932,250 (ASSAF ET AL) 12 June 1990, col. 3 lines 7-19	13
X ---,E Y	US, A, 5,347,876 (KANG ET AL) 20 SEPTEMBER 1994, See Fig.6	14 and 16 ------ 15 and 17
X ----- Y	US, A, 4,346,603 (SCHMID) 31 AUGUST 1982 See fig.9	22 ----- 18-21 and 23
Y	US, A, 4,335,616 (OLIVA ET AL) 22 June 1982, See Fig.1	21
X	US, A, 4,228,683 (JUFFA ET AL) 21 October 1980, See Fig.1	22
Y	US, A, 4,628,743 (MILLER ET AL) 16 DECEMBER 1986, See Fig.3	21
Y ----- A	US, A, 4,685,331 (RENKEN ET AL) 11 AUGUST 1987 See fig.1	2-4 and 7 --------- 11
X	US, A, 4,938,079 (GOLDBERG) 03 July 1990, See col.6 lines 17-44	
X	US, A, 4,995,268 (ASH ET AL) 26 FEBRUARY 1991, See col 3 lines 2-22	18-20
A	US, A, 3,871,229 (FLETCHER) 18 MARCH 1975, See col. 5 lines 22-38	13

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US94/07392

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Please See Extra Sheet.

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest ☐ The additional search fees were accompanied by the applicant's protest.
☐ No protest accompanied the payment of additional search fees.

A CLASSIFICATION OF SUBJECT MATTER:
IPC (5):

G01F 1/68; G01P 5/18; G08B 21/00; F16K 17/00; A61M 31/00; B57D 5/08

BOX II. OBSERVATIONS WHERE UNITY OF INVENTION WAS LACKING
This ISA found multiple inventions as follows:

I. CLAIMS 1-12, DRAWN TO A THERMAL FLOW METER
II. CLAIM 13, DRAWN TO A BUBBLE DETECTOR
III. CLAIMS 14-17, DRAWN TO MULTIPLE FLOW SENSORS
IV. CLAIMS 18-23, DRAWN TO A FLOW DELIVERY SYSTEM

INVENTIONS IV AND III, II, AND I ARE RELATED AS COMBINATION AND SUBCOMBINATION. IN THE INSTANT CASE, THE COMBINATION AS CLAIMED DOES NOT REQUIRE THE PARTICULARS OF THE SUBCOMBINATION AS CLAIMED BECAUSE AS EVIDENCED BY THE LACK OF SPECIFICS OF THE VARIOUS SBBCOMBINATIONS IN COMBINATION CLAIMS 18 AND 22. THE SUBCOMBINATIONS HAVE SEPARATE UTILITY SUCH AS IN SYSTEMS WHICH DO NOT UTILIZE A VALVE FOR CONTROL OF FLUID FLOW. ALSO THE VARIOUS SUBCOMBINATIONS HAVE SEPARATE UTILITY, ALONE OR WITH OTHER COMBINATIONS. I DOES NOT REQUIRE THE MULTIPLE SENSORS OF III OR THE BUBBLE DETECTOR OF II AND IS CAPABLE OF INDEPENDENT USE. III DOES NOT REQUIRE THE BUBBLE DETECTOR OF II AND EACH GROUP HAS UTILITY BY ITSELF.