

SYSTEMS AND METHODS FOR PUMPING CONTINUOUS LIQUID COLUMNS USING HYDROPHOBICITY CONTROL FEATURES IN A MICROCHANNEL

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BACKGROUND OF THE INVENTION

[0001] The present invention relates generally to micropumping systems and methods, and more particularly to systems and methods for pumping ultra-small volume continuous liquid columns using controlled hydrophobicity actuation features in a microchannel.

[0002] In fields such as environmental monitoring, chemical analysis systems, implantable medical devices, drug delivery systems and diagnostic systems, there is a demand for micropumps that can deliver ultra-small volumes of fluids. Traditional micropumps utilize piezoelectric, electrostatic, thermopneumatic or electromagnetic actuators to generate a driving force for moving fluid in the pump. However, piezoelectric and electrostatic actuators typically require a high driving voltage of usually above 100 volts, and thermopneumatic and electromagnetic actuators typically consume a large amount of electric power. Additionally, pumps which use the above actuation mechanisms are also typically relatively bulky in size and cannot be further miniaturized due to the physical size limitations imposed by the components of the actuators. Further, the smallest quantum of liquid that can be pumped using pumps presently available are in the range of a few nanoliters (nl).

[0003] Therefore, micropumps based on such prior actuation mechanisms are undesirable for use in systems requiring low power consumption, small size and controlled delivery of small quanta of liquid volume. For example, micropumps using these actuation mechanisms are undesirable for use in remote environmental monitoring systems, implantable medical devices, chemical analysis systems and other systems which need pumps that are small, consume less power (e.g., operate at a low voltage) and are capable of pumping very small quanta of liquid volume.

[0004] It is therefore desirable to provide micropumps that overcome the above and other problems. Such pumps should also provide controlled volumes of liquid in the sub-nanoliter range.

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BRIEF SUMMARY OF THE INVENTION

[0005] The present invention provides micropumps that overcomes the above problems. In particular, the present invention provides systems and methods for pumping ultra-small volume continuous liquid columns in a microchannel using controlled hydrophobicity actuation features in the microchannel.

[0006] According to the present invention, a micropump includes a microchannel formed in a substrate. The microchannel includes a plurality of electrode ring layers or electrodes with other geometries within the microchannel. Alternating electrode layers are covered with a fluoropolymer or a layer of self assembled monolayer or other hydrophobic substance that changes to a hydrophilic state in response to an applied voltage signal. Electrodes covered by fluoropolymer material or self assembled monolayer define hydrophobic regions interspersed between hydrophilic regions defined by exposed hydrophilic substrate material or electrode ring layers or electrodes with other geometries. The covered electrodes in the hydrophobic regions may include the same or different materials as the exposed electrodes in the hydrophilic regions. When a fluid within the microchannel nears a hydrophobic region, a meniscus formed by the fluid is prevented from propagating due to the hydrophobic properties of the microchannel surface in that region. Application of a voltage signal between the fluid (via an exposed electrode) and the electrode in the hydrophobic region causes the hydrophobic material overlaying that electrode to become hydrophilic, thereby allowing the meniscus, and the column of fluid behind it, to propagate past that region due to capillary forces. Upon encountering the next hydrophobic region, the meniscus is again prevented from propagating. The region that was changed from hydrophobic to hydrophilic may revert back to its natural hydrophobic state gradually, for example after the voltage signal has ceased, however, this will have no effect on the column of liquid that has passed. Selective application of voltage signals to the electrodes in consecutive hydrophobic regions allows for a controlled rate of flow of fluid columns as determined by the dimensions of the microchannel (e.g., diameter of a microchannel having a circular cross-section) and properties of the propagating fluid (e.g., viscosity). Also, controlled reversal of the voltage signal can be used to controllably revert the region back to a hydrophobic state. This allows for a hydrophobic region to operate as a valve after fluid has passed; reverting back to hydrophobic cuts off the fluid flow.

[0007] In certain aspects, the micropumps of the present invention advantageously do not employ actuators having physical components that would limit minimum device sizes, and

therefore can be miniaturized as desired for the particular application. The limitation to miniaturization is only imposed by the limitations in current lithography techniques (*i.e.*, the smallest feature size that can be defined using current lithography techniques). For example, if the lithography process used in making a micropump is capable of defining 100 nanometer (nm) features, then the size of features of the pump will be on the order of a few hundred nanometers. When using 100nm lithography, a pump according to the present invention is capable of pumping quanta of liquids as small as a few atto liters. Further, pumps according to the present invention can be used to pump liquid quanta as large as a few ml or greater. The voltage required to pump liquids using controlled hydrophobicity actuation features of the present invention is advantageously less than about 20 Volts, *e.g.*, 5 Volts or less, at an extremely low current (*e.g.*, on the order of a few 10s' of mA or lower).

[0008] The controlled hydrophobicity actuation utilizes surface tension as a driving force in the micro-nano scale. Therefore, pumps according to the present invention do not require a dedicated actuator for pumping. Also, in certain aspects, these pumps include an in-built metering feature that is useful to pump a measured volume of liquid. This measured volume can be selected to be in the range of a few milliliters to a few attoliters. The pump design of the present invention presents a new micro/nano fluidic device design and therefore also presents a variety of new applications. For example, the low power consumption and low voltage requirements of these pumps make them very attractive for applications that require an ultra miniature metering pump which operates at a low voltage.

[0009] According to one aspect of the invention, a micropump is provided that typically includes a fluid channel having an inner surface and defining an axis of fluid propagation. The micropump also typically includes a first electrode ring disposed on the inner surface of the fluid channel around the axis, a second electrode ring disposed on the inner surface of the fluid channel around the axis, and a layer of hydrophobic material overlaying the second electrode ring. Upon application of a voltage to the second electrode ring, the hydrophobic material becomes hydrophilic.

[0010] According to another aspect of the invention, a micropump is provided that typically includes a fluid channel having an inner surface and defining an axis of fluid propagation. the micropump also typically includes a plurality of first electrode rings disposed on the inner surface of the fluid channel around the axis, a plurality of second electrode rings disposed on the inner surface of the fluid channel around the axis and the second electrode rings are

interspersed between the plurality of the first electrode rings, and a layer of hydrophobic material overlaying each second electrode ring such that alternating hydrophobic and hydrophilic regions are encountered along the axis. Upon application of a voltage to a selected one of said second electrode rings, the hydrophobic material overlaying the selected electrode becomes hydrophilic.

[0011] When a fluid is present in a fluid channel, a hydrophobic layer prevents a meniscus formed by the fluid from propagating along said axis, and when a voltage is applied to a second electrode ring and the hydrophobic material becomes hydrophilic, capillary forces move the meniscus past the region defined by the material overlying that second ring. In certain aspects, the hydrophobic material overlying a second electrode includes a fluoropolymer such as CYTOP or Teflon. Also, in certain aspects, the fluid channel is formed in a substrate material such as silicon, silicon nitride, quartz, glass, or an insulated metal, plastic, dielectric, conductor or semiconductor or other insulated material.

[0012] According to a further aspect of the present invention, a method is provided for delivering controlled amounts of fluid. The method typically includes coupling a fluid source to a fluid channel having an inner surface, with the fluid channel defining an axis of fluid propagation. The fluid channel typically includes a plurality of first electrode rings disposed on the inner surface of the channel around the axis, a plurality of second electrode rings disposed on the inner surface of the channel around the axis and the second electrode rings are interspersed between the plurality of the first electrode rings, and a layer of hydrophobic material overlaying each second electrode ring such that alternating hydrophobic and hydrophilic regions are encountered within the fluid channel along the defined axis. The method also typically includes applying voltages to consecutive selected ones of the second electrode rings so as to cause the hydrophobic material overlaying the selected second electrode rings to become hydrophilic, wherein a meniscus formed by the fluid in the fluid channel is prevented from passing a hydrophobic region, and wherein capillary forces move the meniscus past the regions defined by the selected second electrode rings so as to move a volume of fluid defined by the number of selected second electrode rings.

[0013] Reference to the remaining portions of the specification, including the drawings and claims, will realize other features and advantages of the present invention. Further features and advantages of the present invention, as well as the structure and operation of various embodiments of the present invention, are described in detail below with respect to the

accompanying drawings. In the drawings, like reference numbers indicate identical or functionally similar elements.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] FIG. 1 illustrates various views of a pump design implemented with a circular cross-section microchannel according to one embodiment.

[0015] FIGS. 2a-h show side cross-sectional views of fluid propagating in a fluid channel including multiple alternating hydrophobic and hydrophilic regions according to the present invention.

[0016] FIG. 3 is a photograph of side view of a fabricated pump according to the present invention.

[0017] FIG. 4 shows a series of snapshots taken of the pump in FIG. 3 when actively pumping fluid.

[0018] FIG. 5 illustrates a process flow for fabricating a pump channel according to the present invention.

[0019] FIG. 6 shows a side view of a flat rectangular electrode formed on a substrate and covered with a hydrophobic material.

DETAILED DESCRIPTION OF THE INVENTION

[0020] FIG. 1 illustrates various views of a pump design implemented with a circular cross-section microchannel according to one embodiment. The pump includes a channel 10 (fluid channel) formed in a substrate material 15. The fluid channel 10 is in fluid communication with a fluid source (not shown) such as a liquid reservoir. Fluid from the fluid source enters the fluid channel 10 and propagates by capillary force. As shown in FIG. 1a, at least a portion of the fluid channel includes alternating rings of hydrophobic and hydrophilic areas, or regions, disposed on the inside wall.

[0021] FIG. 1b shows a cross-sectional view of a hydrophobic region of fluid channel 10. The hydrophobic region includes a layer of hydrophobic material 20 overlying a conductive

electrode 25, e.g., Au or Pt electrodes. Each hydrophobic region can be made to become hydrophilic by applying an electric field across the electrode that lies underneath the hydrophobic material and the fluid in channel 10. One or more conductive electrodes 30, e.g., Au or Pt electrodes, are also positioned in the channel outside the hydrophobic areas.

5 These electrodes 30 will be referred to herein as bare or exposed electrodes 30, and can be in contact with a fluid in the fluid channel unlike the electrodes 25 in the hydrophobic regions, which are preferably completely underneath hydrophobic layers or films 20. In one aspect, the electrode 25 underneath the hydrophobic area is connected to the positive terminal of a power supply while the exposed electrode 30 is connected to the negative terminal as shown
10 in FIG. 1c.

[0022] When fluid is present in the fluid channel, a hydrophobic region prevents a meniscus formed by the fluid, and also the fluid column behind it, from propagating past the region. When no voltage is applied, the hydrophobic region remains hydrophobic. When a voltage signal is applied between the fluid (via an exposed electrode) and the electrode 25
15 underlying this hydrophobic region, the hydrophobic material becomes hydrophilic and the fluid column propagates in the fluid channel 10 until it meets the next hydrophobic region, at which point the meniscus is prevented from passing and the fluid column stops propagating. The fluid column propagates primarily due to capillary force, and it automatically gets rid of any unwanted air bubbles present in the system.

20 [0023] FIG. 2 show side cross-sectional views of fluid column 40 propagating in a fluid channel 10 including multiple alternating hydrophobic and hydrophilic regions according to the present invention. Hydrophobic regions are defined by the hydrophobic film 20 overlying an electrode 25 (not shown in FIG. 2), and hydrophilic regions are defined by the regions not covered by a hydrophobic material. Exposed electrodes 30 are located in the hydrophilic
25 regions as shown. In one aspect, only one exposed electrode 30₁ need be used. However, it is preferred that multiple exposed electrodes 30 be positioned throughout the channel and interspersed between the hydrophobic regions to reduce the actuation voltage needed for each hydrophobic region. For example, in one embodiment, exposed electrodes 30 are interspersed between hydrophobic regions so as to form exposed-covered electrode pairs.
30 One skilled in the art will understand that differing numbers of exposed and covered electrodes may be used, such as one exposed electrode for every two (or more) covered electrodes. In such cases, it may be useful to apply different voltages between the covered electrodes and the exposed electrode depending on the distance from the exposed electrode.

[0024] As shown in FIG. 2a, the meniscus 45 of a propagating fluid column 40 extends with a contact angle 50 relative to the inner walls of the fluid channel 10 when propagating in a hydrophilic region. The contact angle 50 formed by the meniscus 45 is a function of the interfacial surface tension between the fluid and surface, the surface tension between the fluid and atmosphere (air, gas or liquid in channel surrounding meniscus) and the surface tension between the atmosphere and surface. When the meniscus 45 reaches a hydrophobic region 20, the meniscus 45 forms a contact angle 55 relative to the inner walls of the fluid channel 10 as shown in FIG. 2b. This contact angle 55 is formed by the surface tension between the hydrophobic surface, the fluid and the air at the interface between the hydrophobic region and the hydrophilic region. The meniscus 45, and thus the column of fluid 40 behind the meniscus, is prevented from propagating in the fluid channel due to the properties of the hydrophobic material in the hydrophobic region. As can be seen, the meniscus changes between a concave and a convex profile depending on whether the fluid is propagating or held by a hydrophobic region.

[0025] To control propagation of the meniscus past this region, a voltage signal may be applied to the electrodes 25 and 30 as shown in FIG. 2c to change this hydrophobic region to a hydrophilic state. Upon application of a voltage, e.g., 5V, the hydrophobic material overlying the electrode 25 becomes hydrophilic, and the meniscus again propagates down the fluid channel. The angle formed at the contact with the inner walls of the fluid channel changes due to the (now) hydrophilic state of this region as shown in FIG. 2d. After the fluid column 40 has passed, a region that was changed to a hydrophilic state may revert back to its natural hydrophobic state. However, reverting back to the hydrophobic state will have little or no effect on the portion of fluid column 40 that has passed as the meniscus 45 has already passed this region. In certain aspects, the voltage applied to an electrode 25 may be turned off or reversed after passage of the meniscus. This allows for the fluid flow in channel 10 to be controllably shut off at that hydrophobic region. For example, upon reverting back to a hydrophobic state that region 30 will cut off fluid flow and a new meniscus will form at the hydrophobic-hydrophilic interface. Unless stopped by another hydrophobic region, fluid that has already passed will continue to propagate in channel 10 due to capillary forces.

[0026] Similar to FIGS 2a-d, FIGS. 2e-h show the meniscus 45, and fluid column 40, propagating further through the fluid channel 10 (FIG. 2e), encountering the next hydrophobic region (FIG. 2f), which is selectively converted to a hydrophilic state (FIG. 2g) to allow the meniscus and fluid column to pass (FIG. 2h). In this manner, propagation of a

column of fluid can be controlled by selectively controlling the states of interaction of each hydrophobic region encountered by the fluid column in the fluid channel. For example, a continuous flow of fluid can be precisely controlled and pumped. Also, any ionic fluid such as water or a solution of ionic salt desolated in water may be pumped using the pumps of the present invention.

[0027] According to one embodiment, a method of pumping or delivering fluid includes coupling a fluid source such as a liquid reservoir to a fluid channel as described above. The fluid channel includes an inner surface that defines an axis of fluid propagation. The fluid channel typically includes one or more exposed electrode rings disposed on the inner surface of the channel around the axis and a plurality of second electrode rings disposed on the inner surface of the channel around the axis with a layer of hydrophobic material overlaying each second electrode ring. The exposed inner surface and the exposed electrode ring(s) on the inner surface are preferably hydrophilic. If multiple exposed electrodes are included, the exposed electrodes are preferably interspersed between the plurality of covered electrode rings (e.g., one exposed electrode between every two covered electrodes). Because a layer of hydrophobic material overlays each second electrode ring, alternating hydrophobic and hydrophilic regions are encountered by a fluid propagating within the fluid channel along the axis. A meniscus formed by the fluid in the fluid channel is prevented from passing the first hydrophobic region it encounters.

[0028] The method also typically includes applying voltages to consecutive selected ones of the second electrode rings, beginning with the electrode ring underlying the first hydrophobic region so as to cause the hydrophobic material overlaying the selected second electrode rings to become hydrophilic. Capillary forces move the meniscus past the regions defined by the selected second electrode rings so as to move a volume of fluid defined, in part, by the number of selected second electrode rings to which a voltage is applied. Depending on the relevant dimensions of the fluid channel, the fluid volume delivered can range from one or a few attoliters up to picoliters, nanoliters, milliliters, etc. The fluid flow can be stopped, if desired, by using an integrated valve or by cutting off the source.

[0029] In preferred aspects, a fluid channel is formed in a silicon substrate using standard photolithography techniques. Other useful substrate materials include an insulated metal, a insulated non-metal, an insulated semiconductor and an insulator. Specific examples include silicon, silicon nitride, quartz, glass and others. It should be appreciated that other materials

as would be apparent to one skilled in the art may be used. A fluid channel according to the present invention preferably has a circular cross-section as shown, for example in FIG. 1. However, it should be appreciated that a fluid channel may have any cross-sectional geometry such as, for example, oval or elliptical, square, rectangular, triangular, hexagonal, etc. Further, the fluid channel, in certain aspects should have dimensions suitable for the particular application. For example, in one circular cross-section embodiment, the fluid channel has a diameter of about 100 μm or less. It should be appreciated that the diameter (or relevant dimension of other cross sectional geometry channels) can range down to the limits of photolithography processing (e.g., currently on the order of 100 nm) up to the mm or cm range.

[0030] In preferred aspects, CYTOP Fluoropolymer is used for the hydrophobic layer(s) material and gold (Au) is used for the electrodes. In general, useful materials for the hydrophobic layer(s) include any insulating material that has a sufficiently high dielectric constant, e.g., to allow for the reversal back to a hydrophobic state upon application of an appropriate inverse voltage signal. Examples include a fluoropolymer such as CYTOP, Teflon, PTFE, PFA, FEP, ETFE, CTEE and others, as well as other materials such as ceramics, oxides, nitrides, oxynitrides, etc. Useful materials for the electrodes include conductive metals, semiconductors and conductive polymers. Examples include Au, Pt, Al and other metals, as well as other materials such as Si, polyaniline, polythiophene, polyphenylenevinylene, etc. It should be appreciated that the material used for the electrodes may differ between electrodes. For example, the exposed electrodes may include materials different from the materials used for the covered electrodes. Additionally, the materials used for different covered or exposed electrodes may also vary. It is preferred that the electrodes are made of hydrophilic material to prevent them from affecting fluid flow, although the covered electrodes may be made of a hydrophobic material if desired.

[0031] The dimensions of electrodes and spacings between electrodes may also vary. In preferred aspects, the exposed and covered electrodes will have thicknesses ranging from about 100 nm or smaller to about 1 μm or greater, and widths ranging from about 10 nm or smaller to about 1 mm or greater, preferably between about 100 nm and about 10 μm . The widths and thicknesses may vary from electrode to electrode. Further, in preferred aspects, the exposed and covered electrodes are typically displaced from each other by a distance ranging from about 1 nm to about 10 nm or greater. In one aspect, the distance between exposed - covered electrode pairs is substantially the same throughout the fluid channel, and

the distance between an exposed electrode and a covered electrode within an electrode pair is substantially the same for electrode pairs throughout the fluid channel. However, these distances may vary between and among electrode pairs throughout a fluid channel. For example, the interspacing distance between electrode pairs or within an electrode pair may vary depending on the dimensions of an overlying hydrophobic material layer.

[0032] According to one aspect, a hydrophobic layer has a width in the range of about 1 nm (nanometers) or smaller to about 10 mm (millimeters) or greater depending on the dimensions of the fluid channel and the desired pump application. Further, in one aspect, a hydrophobic layer has a thickness of between about 1 nm or smaller and about 100 nm or greater. In general, the dimensions of a hydrophobic layer required will depend, in part, on the material used, the dimensions of the fluid channel and the desired application of the pump. Likewise, the dimensions and materials of an underlying electrode may depend, in part, on the dimensions and materials of the overlying hydrophobic layer. The width of an electrode underlying a hydrophobic film layer is preferably smaller than the width of the film layer. For example, in one embodiment, the underlying electrodes are about 2 μm to about 5 μm shorter (narrower) than the hydrophobic film layer. The dimensions of the electrodes will determine the applied potential, the time it takes for the contact angle of the meniscus to change, and generally the pump performance. Thus, one skilled in the art will readily understand useful electrode and hydrophobic region configurations and materials.

[0033] Advantageously, pumps according to the present invention are able to operate using applied voltages below about 30 Volts, and preferably below 20 Volts. In certain aspects, voltages around 5 Volts or lower may be applied between an exposed electrode and a covered electrode to convert the overlying hydrophobic material to a hydrophilic state. In general, a pump according to the present invention can be operated at a lower voltage by optimizing the thickness of the hydrophobic layer. Also, it is preferred that covered and exposed electrodes be positioned in close proximity so as to reduce the needed actuation voltage. However, as above, an exposed electrode may be used with more than one covered electrode. Further, pumps according to the present invention can be used to pump any ionic liquid.

[0034] One example of a process to form a pump, e.g., fluid channel in a substrate including the actuation features (e.g., electrodes and hydrophobic layers), of the present invention will be described below with reference to FIG. 5, which shows a process for fabricating a rectangular cross section channel. It will be appreciated by one skilled in the art

that channels having other cross-sectional geometries can be fabricated using similar techniques with minor modifications.

[0035] In the example shown in FIG. 5, standard silicon/glass microfabrication

technologies are used to fabricate the microchannels. First, silicon and glass wafers are

5 cleaned using standard cleaning techniques. For a microchannel, a photoresist is spin coated on the silicon wafer, then exposed with a photomask containing the microchannel pattern.

After developing, the microchannel pattern is transferred to the photoresist. Etching, e.g.,

BHF etching, is used to remove SiO_2 on the patterned area. Thereafter, using wet etching

(e.g., KOH, 40%+60°C), the channel is etched to the desired depth, e.g., to be about 100 μm

10 deep. For the electrodes on glass, a photolithography process is used to transfer the pattern onto photoresist which is on glass. Electrodes are formed by sputtering Cr (e.g., 100 nm

thick) and Au (e.g., 200 nm thick) onto the wafer. Lift-off is then performed to obtain the

patterned electrodes. The hydrophobic material, e.g., CYTOP, may then be deposited, e.g.,

spin coated, exposed, developed and etched as is well known. For example, FIG. 6 shows a

15 side view of a flat rectangular electrode formed on a substrate and covered with a

hydrophobic material. It should be appreciated that the above is only an example of a

possible method to create a fluid channel and that other additional or alternative materials,

parameters and process steps may be used as desired.

[0036] FIG. 3 is a photograph of a side view of a fabricated pump according to the present

20 invention. As shown, the pump includes a fluid channel and a plurality of electrode rings

covered with CYTOP. A plurality of exposed electrode rings adjacent the covered electrodes

are also shown. The channel width, depth and the electrode spacing are in the range of a few

nm to a few mm. FIG. 4 shows a series of snapshots taken of the pump in FIG. 3 when

actively pumping fluid. As shown, the direction of fluid flow is from left to right in the fluid

25 channel. Upon application of a voltage potential between the covered and exposed

electrodes, the meniscus of the fluid passes across the region defined by the CYTOP covered electrode.

[0037] It will be understood that various modification to the pumps of the present invention are within the scope of the present invention. For example, the electrode rings can be

30 replaced by electrodes having other geometries, e.g., for a channel having a cross-section of a rectangle, the electrodes can be made to be rectangular and flat.

[0038] In one embodiment, a hydrophobic coating includes a self assembled monolayer (SAM). By applying an electric field between the electrode and the fluid inside the channel, the hydrophobic SAM is removed (e.g., dissolved) which exposes the hydrophilic electrode, thereby allowing the capillary effect to move the fluid. This process is reversible; by
5 providing an appropriate reversed bias voltage, the SAM coating can be assembled or reassembled to produce the hydrophobic region. In another embodiment, the coatings on the hydrophobic area include a thin film having low dielectric breakdown voltage. When the dielectric breaks down the hydrophobic surface becomes hydrophilic and the liquid propagates through the channel. This process is generally not reversible.

10 [0039] While the invention has been described by way of example and in terms of the specific embodiments, it is to be understood that the invention is not limited to the disclosed embodiments. To the contrary, it is intended to cover various modifications and similar arrangements as would be apparent to those skilled in the art. For example, one skilled in the art will understand that the pumps of the present invention can be used to pump fluid forward
15 and backward in a channel using the controlled hydrophobicity actuation features of the present invention. Further, fluid channels (with or without actuation features) having different geometries and/or dimensions can be fluidly coupled in series. Also, electrodes, whether exposed or covered, need not surround the channel, for example they may cover only a portion of a circular channel or only one side of a rectangular channel. Therefore, the scope
20 of the appended claims should be accorded the broadest interpretation so as to encompass all such modifications and similar arrangements.

WHAT IS CLAIMED IS:

- 1 1. A micropump, comprising:
2 a fluid channel having an inner surface and defining an axis of fluid
3 propagation;
4 a first electrode ring disposed on the inner surface around said axis;
5 a second electrode ring disposed on the inner surface around said axis; and
6 a layer of hydrophobic material overlaying the second electrode ring, wherein
7 application of a voltage between the first electrode ring and the second electrode ring when a
8 fluid is present in the channel causes the hydrophobic material to become hydrophilic.
- 1 2. The micropump of claim 1, wherein when the fluid is present in the
2 fluid channel, the hydrophobic layer prevents a meniscus formed by said fluid from
3 propagating along said axis, and wherein when the voltage is applied to the second electrode
4 ring and the hydrophobic material becomes hydrophilic, capillary forces move the meniscus
5 past the region defined by the second ring. Voltage is applied between the electrode and
6 liquid.
- 1 3. The micropump of claim 1, wherein the hydrophobic material includes
2 an insulating material having a substantially high dielectric constant.
- 1 4. The micropump of claim 1, wherein the hydrophobic material includes
2 a fluoropolymer.
- 1 5. The micropump of claim 4, wherein the fluoropolymer is selected from
2 the group consisting of CYTOP, Teflon and zirconium oxynitride.
- 1 6. The micropump of claim 1, wherein the fluid channel is formed in a
2 substrate material selected from the group consisting of silicon, silicon nitride, quartz,
3 polymer, plastic and glass.
- 1 7. The micropump of claim 1, wherein the fluid channel is formed in a
2 substrate material selected from the group consisting of an insulated metal, an insulated non-
3 metal, an insulated semiconductor, a dielectric, ceramic, an insulated conductor and an
4 insulator.

1 8. The micropump of claim 1, wherein the first electrode ring includes a
2 conductive material selected from the group consisting of a metal, a semiconductor, a
3 ceramic and a conductive polymer.

1 9. The micropump of claim 1, wherein the first electrode ring includes a
2 metal selected from the group consisting of Au and Pt.

1 10. The micropump of claim 1, wherein the second electrode ring includes
2 a conductive material selected from the group consisting of a metal, a semiconductor, a
3 ceramic and a conductive polymer.

1 11. The micropump of claim 1, wherein the second electrode ring includes
2 a different material than the first electrode ring.

1 12. The micropump of claim 1, wherein the first and second electrode
2 rings are displaced between about 1 nm and about 10 nm from each other within the fluid
3 channel.

1 13. The micropump of claim 1, wherein the hydrophobic layer has a width
2 in the range of about 0.1 nm to about 10 nm, and a thickness in the range of about 1 nm to
3 about 100 nm.

1 14. The micropump of claim 1, wherein the voltage applied to the first ring
2 and the second ring ranges from 30V to 0.1V.

1 15. The micropump of claim 1, wherein the fluid channel has a cross
2 section geometry selected from the group consisting of circular, rectangular, elliptical,
3 hexagonal, and octagonal.

1 16. The micropump of claim 15, wherein the circular cross section of the
2 fluid channel has a diameter of less than about 100 μm .

1 17. A micropump, comprising:
2 a fluid channel having an inner surface and defining an axis of fluid
3 propagation;
4 one or more first electrode rings disposed on the inner surface around said
5 axis;

6 a plurality of second electrode rings disposed on the inner surface around said
7 axis, wherein said second electrode rings are interspersed between said one or more first
8 electrode rings; and

9 a layer of hydrophobic material overlaying each second electrode ring such
10 that alternating hydrophobic and hydrophilic regions are encountered along said axis, wherein
11 application of a voltage between one of said first electrode rings and a selected one of said
12 second electrode rings when a fluid is present in the fluid channel causes the hydrophobic
13 material overlaying said selected electrode to become hydrophilic.

1 18. The micropump of claim 17, wherein when the fluid is present in the
2 fluid channel, a hydrophobic layer prevents a meniscus formed by said fluid from passing,
3 and wherein when the voltage is applied to the selected second electrode ring and the
4 overlaying hydrophobic material becomes hydrophilic, capillary forces move the meniscus
5 past the region defined by the selected second electrode ring.

1 19. The micropump of claim 17, wherein a controlled volume of fluid is
2 pumped through the micropump as determined by a number of consecutive second rings that
3 are activated by application of a voltage.

1 20. The micropump of claim 17, wherein the hydrophobic material
2 includes a dielectric or insulated materials.

3 21. The micropump of claim 17, wherein the hydrophobic material
4 includes a fluoropolymer.

1 22. The micropump of claim 21, wherein the fluoropolymer is selected
2 from the group consisting of CYTOP, Teflon and zirconium oxynitride.

1 23. The micropump of claim 17, wherein the fluid channel is formed in a
2 substrate material selected from the group consisting of an insulated metal, an insulated non-
3 metal, an insulated semiconductor and insulated conductor and an insulator.

1 24. The micropump of claim 17, wherein the fluid channel is formed in a
2 substrate material selected from the group consisting of silicon, silicon nitride, quartz and
3 glass.

1 25. The micropump of claim 17, wherein each first electrode ring includes
2 a conductive material selected from the group consisting of a metal, a semiconductor and a
3 conductive polymer.

1 26. The micropump of claim 17, wherein each first electrode ring includes
2 a metal selected from the group consisting of Au and Pt.

1 27. The micropump of claim 17, wherein each second electrode ring
2 includes a conductive material selected from the group consisting of a metal, a semiconductor
3 and a conductive polymer.

1 28. The micropump of claim 17, wherein one or more second electrode
2 rings include a different material than one or more of the first electrode rings.

1 29. The micropump of claim 17, wherein consecutive first and second
2 electrode rings are displaced between about 1 nm and about 10 nm from each other within the
3 fluid channel.

1 30. The micropump of claim 17, wherein each hydrophobic layer has a
2 width in the range of about 0.1 nm to about 10 nm, and a thickness in the range of about 1
3 nm to about 100 nm.

1 31. The micropump of claim 17, wherein the voltage applied to a first ring
2 and each selected second ring is in the range of from 30V to 0.1V.

1 32. The micropump of claim 17, wherein the fluid channel has a cross
2 section geometry selected from the group consisting of circular, rectangular, elliptical,
3 hexagonal, and octagonal.

1 33. The micropump of claim 32, wherein the cross section of the fluid
2 channel has a diameter of less than about 100 μm .

1 34. A method of delivering controlled amounts of fluid, the method
2 comprising:
3 coupling a fluid source to a fluid channel having an inner surface, said fluid
4 channel defining an axis of fluid propagation, wherein said fluid channel further include:

5 one or more first electrode rings disposed on the inner surface around
6 said axis;

7 a plurality of second electrode rings disposed on the inner surface
8 around said axis and interspersed between said one or more first electrode
9 rings; and

10 a layer of hydrophobic material overlaying each second electrode ring
11 such that alternating hydrophobic and hydrophilic regions are encountered
12 within the fluid channel along said axis; and

13 applying a voltage between selected ones of said first electrodes and
14 consecutive selected ones of said second electrode rings so as to cause the hydrophobic
15 material overlaying said selected second electrode rings to become hydrophilic, wherein a
16 meniscus formed by the fluid in the fluid channel is prevented from passing a hydrophobic
17 region, and wherein capillary forces move the meniscus past the regions defined by the
18 selected second electrode rings so as to move a volume of fluid defined by the number of
19 selected second electrode rings.

1 35. The method of claim 34, wherein the fluid channel has a cross section
2 geometry selected from the group consisting of circular, rectangular, elliptical, hexagonal,
3 and octagonal.

1 36. The method of claim 35, wherein the cross section of the fluid channel
2 has a diameter of less than about 100 μm .

1 37. The method of claim 34, wherein consecutive first and second
2 electrode rings are displaced between about 1 nm and about 10 nm from each other within the
3 fluid channel.

1 38. The method of claim 34, wherein each hydrophobic layer has a width
2 in the range of about 0.1 nm to about 10 nm, and a thickness in the range of about 1 nm to
3 about 100 nm.

1 39. The method of claim 34, wherein the voltage applied to a first
2 electrode and each selected second ring ranges from 30V to 0.1V.

1 40. The method of claim 34, wherein spacing between consecutive second
2 electrode rings varies, and wherein the volume of fluid moved is based on the spacing
3 between selected second rings.

1 41. The micropump of claim 1, further comprising a voltage source for
2 providing the voltage to the first and second electrodes.

1 42. The micropump of claim 17, further comprising a voltage source for
2 providing the voltage to the first electrode and the selected second electrodes.