Method and system for rapid and accurate determination of each of a sequence of unknown polymer components, such as nucleic acid components. A self-assembling monolayer of a selected substance is optionally provided on an interior surface of a pipette tip, and the interior surface is immersed in a selected liquid. A selected electrical field is impressed in a longitudinal direction, or in a transverse direction, in the tip region, a polymer sequence is passed through the tip region, and a change in an electrical current signal is measured as each polymer component passes through the tip region. Each of the measured changes in electrical current signals is compared with a database of reference electrical change signals, with each reference signal corresponding to an identified polymer component, to identify the unknown polymer component with a reference polymer component. The nanopore preferably has a pore inner diameter of no more than about 40 nm and is prepared by heating and pulling a very small section of a glass tubing.
Fig. 1A

Fig. 1B
Fig. 1C

Fig. 2A (Polymer Absent)
Provide pipette with pore having a selected SAM positioned on pore interior surface

Provide a selected ionizable liquid in pore interior

Impress longitudinal electrical field \( E_{\text{long}} \) across selected liquid in pore

Pass (unknown) polymer components sequentially through pore and measure ionic current signal for each polymer component

Compare each of sequence of measured ionic current change signals \( CIC(t;\text{meas}) \) with reference change signals \( CIC(t;\text{ref};n) \) in a reference database

Assign each polymer component in unknown sequence to reference polymer component, based on signal comparison

---

**Fig. 3**
Compute error $\epsilon(n)$

Determine surviving collection $SC$ of reference change signals $CEC(t, ref, n)$

Is $SC$ an empty set?

YES

Assign special symbol (e.g., LINK) to corresponding unknown polymer component

NO

Identify each reference change signal in the surviving collection $SC$

Identify at least one reference polymer component, whose corresponding reference signal is in $SC$, with the (unknown) polymer component

Fig. 4
Provide pipette with pore having a selected SAM positioned on pore interior surface

Immerse pore interior surface in a selected ionizable liquid

Impress transverse electrical field $E_{\text{(trans)}}$ across selected liquid in pore

Pass (unknown) polymer components through pore and measure electronic current signal for each polymer component as polymer passes through the pore

Compare each of sequence of measured electronic current change signals $CEC(t;\text{meas})$ with reference change signals $CSC(t;\text{ref};n)$ in a reference database.

Assign each polymer component in unknown sequence to reference polymer component, based on signal comparison

Fig. 5
Fig. 6D

Fig. 6E

Fig. 6F
1

RAPID POLYMER SEQUENCER

ORIGIN OF THE INVENTION

The invention described herein was made, in part, by an employee of the United States Government and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

TECHNICAL FIELD

The present invention is a method and system for rapidly and accurately determining an ordered sequence of molecular units, such as bases in a nucleic acid, such as DNA or RNA, and for fabricating a nanopore system to facilitate the sequencing.

BACKGROUND OF THE INVENTION

Nanofabrication techniques offer the possibility to create solid state pores or apertures with diameters and lengths similar to diameters and lengths of single nucleotides or proteins. Solid state nanopores permit use of non-physiological conditions for structural manipulation of biopolymers, such as non-neutral pH levels, high temperatures and/or high voltage differences. Use of a solid state substrate will allow a more straightforward manipulation of surface chemistry in the pore, which may be critical to fine-tune the rate of nucleic acid translocation or the degree of ionic current reduction associated with passage of a polymer, such as a poly-nucleotide through a nanopore.

Kasianowicz et al, in “Characterization of individual polynucleotide molecules through a membrane channel,” Proc. Nat. Acad. Sci. vol. 93 (1996) 195-223, have used a pore of diameter about 1.5 nanometers (nm) in the bacterial α-hemolysin ion channel protein, and have applied an electrical field to drive a negatively charged polynucleotide through the pore from one side to the other, which transiently reduces ionic conductance through the pore. Akeson et al, in “Microsecond Time Scale Discrimination Among Polycytidylic Acids in Homopolymers or as Segments Within Single RNA Molecules,” Biophys. Jour. Vol. 77 (1999) 3227-3233, have shown that polynucleotides of different lengths can be discriminated by time duration of translocation as the nucleotide sequence passes through a pore. Translocation of different nucleotide homopolymers reduces ionic conductance of α-hemolysin by characteristic amounts, which suggests that the individual nucleotides in a heteropolymer could be identified, if passed through a nanopore of appropriate dimensions and composition. However, α-hemolysin has a pore length as long as a sequence of about 20 nucleotides so that discrimination between individual nucleotides using α-hemolysin is not possible.

What is needed is a system that provides rapid and accurate identification of ordered components of a nucleic acid, protein or similar polymer, at rates up to and above one component per µsec. Preferably, the approach should adequately discriminate between the different ordered components present in the polymer and provide accurate ordering, with an acceptable error rate that is controllable by varying the rate at which the polymer components pass through and is read by the system.

SUMMARY OF THE INVENTION

These needs are met by the invention, which provides a system and associated method that relies upon a pore at a pipette tip, having a pore diameter as small as 1-40 nm, preferably containing a selected alkali halide, ammonium compound (e.g., NH₄, N(CH₃)₄), or a suitable ionic organic compound or ionic inorganic compound (e.g., CaSO₄, Mg₆P₂O₁₀). In one embodiment, a voltage difference is impressed, in a longitudinal direction or in a transverse direction, across an ionic liquid within the pore, and a varying ionic current through the pore, or a varying electron current across the pore (referred to collectively as an "electrical current") is measured in response to passage of each of an ordered sequence of polymer components, such as nucleotides in a nucleic acid or proteins, through the pore.

In one embodiment, the method includes steps of:

- providing a pipette having a longitudinal axis and having a tapered region having a pore with a selected pore diameter in a range of 1-40 nanometers (nm);
- providing a selected liquid in contact with an interior surface of the pore;
- impressing a selected voltage difference across the selected liquid within the pipette pore substantially parallel to the pipette longitudinal axis direction, and providing an ionic current value induced by passage of each of the polymer components through the pore. In another embodiment, the voltage difference is impressed transversely, across the pore, and a transverse electronic current, induced in response to passage of each of the polymer components through the pore, is measured.

In another embodiment, a method for producing the pore includes steps of:

- heating a hollow cylinder of a selected pipette material, having first and second cylinder ends, having a longitudinal axis and having a selected initial inner diameter, with a selected heating source for at least one of first and second longitudinal locations for at least one of first and second selected time intervals;
- translating one of the first and second cylinder ends relative to the other of the first and second cylinder ends during a selected third time interval that partly or wholly overlaps at least one of the first time interval and the second time interval; and
- allowing the hollow cylinder to separate into at least first and second pipettes and at least one of the first and second pipettes has a pore with a pore diameter in a range 1-40 nanometers (nm).

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A, 1B and 1C illustrate apparatus for practicing the invention.

FIGS. 2A, 2B and 2C graphical views of typical sequences of ionic or electron current values measured with no polymer component present (2A), and in response to passage of a polymer component through a pore (2B, 2C).

FIGS. 3, 4 and 5 are flow charts illustrating procedures for practicing the invention according to two embodiments.

FIGS. 6A-6F graphically illustrate time variations that can be applied to an impressed voltage difference used in the invention.

FIGS. 7A and 7B illustrate formation of a pipette tip for use in the invention.

DESCRIPTION OF BEST MODES OF THE INVENTION

FIG. 1A illustrates one embodiment of apparatus for measurement of longitudinal ionic current in practicing the inven-
be octadecyltrichlorosilane (C₂₅H₄₃SiCl₃) or "OTS"), as provided with a self-assembling monolayer ("SAM") of a polymer component passing through the pore. One or both of the electrodes, 17A and 17B, are arranged on or adjacent to a perimeter of the pore 13p and an electronic current flows from 18A to 18B in response to imposition of a voltage difference ΔV between these electrodes.

FIG. 1B, illustrating an embodiment for measuring transverse electronic current, is similar to FIG. 1A, except that spaced apart electrodes, 18A and 18B, replacing the electrodes 17A and 17B, are arranged on or adjacent to a perimeter of the pore 13 and an electronic current flows from 18A to 18B in response to imposition of a voltage difference ΔV between these electrodes.

FIG. 1C illustrates a different configuration of the pore 13p, according to the invention. In FIG. 1C, different portions of an end 12c of the tip substantially face each other and define an effective pore length L(pore) that is approximately equal to a thickness of the pipette 12 at an end of the pipette. This configuration is preferred where the pore width d(min) is to be made as small as possible (e.g., less than or equal to 1.5 nm).

In one approach, an interior surface of the pore 13p is left uncoated in practicing the invention. Preferably, the interior surface of the pore 13p is coated or wetted or otherwise provided with a self-assembling monolayer (“SAM”) 21 of a selected material that will manifest hydrogen bonding, van der Waals interaction and/or similar reversible, transient interactions with a class of polymers of interest. The SAM substance provided on an interior surface of the pore 13p may be octadecyltrichlorosilane (C₁₈H₃₃SiCl₃), or “OTS”, as measured by Sagiv in “Organized Monolayers on Solid Surfaces,” J. Amer. Chem. Soc. Vol. 102 (1980) pp. 92-98, or may be another suitable substance that will interact with a polymer component passing through the pore 13p and allow measurement of a modulated ionic current signal or electron current signal that is characteristic of a particular polymer component. Other SAM substances that may be used include alkylsiloxane monolayers, alkylsilanes, trimethoxysilanes, mono-, di- and tri-chlorosilanes, octadecylsilanes, organochlorosilanes, aminosilanes, perfluorodecyltrichlorosilanes and aminopropylethoxysilanes.

From another perspective, a stable SAM can be formed using sulfur-containing absorbates on gold, chlorosilanes or alkoxysilanes on glass, and fatty acids on a metal oxide surface.
having an approximately constant characteristic amplitude for a small time interval that corresponds to the time required for that polymer component to pass through the tip. In FIG. 2C, passage of each polymer unit through the pore is assumed, more realistically, to produce a signal having a characteristic, time varying signal shape, a characteristic average amplitude and a characteristic shape parameter, for a small time interval that corresponds to the time required for that polymer component to pass through the tip.

Where one or more polymer components passes through the pore, translocation will cause the steady ionic current shown in FIG. 2A to change with time in response to passage of the polymer component through the pore and the accompanying translocation. If, for example, the polymer sequence is a nucleic acid, such as DNA (alternatively, RNA), each nucleotide will contain one of the four bases adenine (A), cytosine (C), guanine (G) and thymine (T) (alternatively, adenine, cytosine, guanine and uracil (U) for RNA). Ideally, each of the four bases (for DNA or for RNA) will produce a distinguishable change in ionic current signal as that nucleotide passes through the pipette tip, as suggested in FIG. 2B or FIG. 2C.

Under the influence of an applied voltage difference, negatively charged nucleotides or other polymer units are driven through the pore, and a polynucleotide strand can thus be threaded from one side of a lipid bilayer to the other. A steady electrical current that is present in the pore in the absence of a polymer unit is partly occluded during translocation. In principle, polymer units of different lengths can be distinguished from each other by translocation duration, and several homopolymers of different composition can be distinguished based on characteristic levels of electrical current reduction.

FIG. 3 is a flow chart of a procedure for practicing the invention. In step 31 of FIG. 3, a pipette, having a longitudinal axis and having a tapered tip with an associated pore having a selected pore minimum inner diameter d in a preferred range (e.g., d=1-40 nm) is provided, and a selected self-assembling monolayer (SAM) is optionally provided on some portion of the pore surface. In step 32, a selected first liquid containing ions is provided in the interior surface of the pore, preferably containing an alkali halide, ammonium compounds (e.g., NH₄, N(CH₃)₄), or a suitable ionic organic compound or ionic inorganic compound (e.g., CaSO₄, Mg₆(PO₄)₄). More generally, the selected first liquid may be any solution that provides a concentration p of ions at least equal to a threshold value ρ(ion; thr), for example, p(ion; thr)≥10⁻⁶ cm⁻³. The liquid may include the polynucleotide or other polymer that is to be identified. In step 33, a voltage difference having a value in a range ΔV=10-2000 milliVolts is impressed on the liquid in the pore, in a direction substantially parallel to the pipette longitudinal axis. If the polymer has a net electrical charge, the polarity of the voltage difference is chosen to induce the polymer to pass through (or across) the pore. In step 34, ordered components in a polymer (unknown) are sequentially passed through the pore, and each of a sequence of changes in ionic current signals is measured, resulting in a sequence of measured values such as the sequences shown in FIG. 2B or FIG. 2C.

In step 35 (optional), the sequence of changes in measured ionic current signals CIC(t; meas) is compared, one-by-one or in consecutive groups, with reference change signals CIC(t; refa), numbered n=1, . . . , N (N=2) in a reference signal database. Each reference change signal corresponds to a reference polymer component. In step 36 (optional), each polymer component (e.g., a nucleotide containing a particular base) in the unknown sequence is assigned to the reference polymer component having a reference ionic current change signal that is most similar, in some quantitative sense, to the measured (changes in) ionic current change signal. Optionally, steps 35 and 36 are performed off-line.

The signal comparison step 35 is optionally implemented as follows. The ionic current change signal CIC(t; meas) for the unknown polymer sequence is measured at a sequence of time values tᵢ, producing a sequence of measured ionic current change values {CIC(tᵢ; meas)}ᵢ (m=1, . . . , M; M=2). This sequence of measured ionic current change values is compared with a reference sequence (n) of ionic current change signal values {CIC(tᵢ; refm(n); meas)}ᵢ, where τ(n) is a selected time shift that may vary with the reference number n being considered, by computing an error value

\[ M \]

\[ m=1 \]

\[ e(n)=\left[ \frac{1}{2} \sum_{m=1}^{M} \left( \frac{CIC(tᵢ;refm(n)); meas)}{CIC(tᵢ;refm(n)); meas)} - e(\text{thr}) \right) \right]^{1/2}, \]

where \( w_m \) is a selected sequence of non-negative weight values (at least one positive) and \( p \) is a selected positive number (e.g., \( p=1, 1.6 \) or 2). Reference ionic current change signals CIC(tᵢ; refm(n); meas) for which the error satisfies \( e(n)\leq e(\text{thr}) \), where \( e(\text{thr}) \) is a selected positive threshold value, are discarded and not considered further for this measured ionic current change value sequence \( CIC(tᵢ; meas) \). When at least one error value satisfies \( e(n)\leq e(\text{thr}) \), the "surviving collection"

\[ SC\{CIC(tᵢ;refm(n); meas)\} \]

of all reference signals with error values that satisfy the inequality \( e(n)\leq e(\text{thr}) \), are considered, and the reference ionic current change signal CIC(tᵢ; refm(n); meas) that provides the smallest error \( e(n) \) is assigned to the unknown polymer unit. When the surviving collection SC is an empty set, because no error value satisfies \( e(n)\leq e(\text{thr}) \), the system assigns a selected symbol, such as UNK, to this polymer unit.

The comparison procedure can be summarized in a flow chart in FIG. 4. In step 41, the error \( e(n) \), defined as in Eq. (1) or in another suitable manner, for each reference change signal CIC(tᵢ; refm(n); meas) in the database is computed. In step 42, the surviving collection SC of reference signals is determined. In step 43, the system determines if SC is an empty set. If the answer to the query in step 43 is "yes," the system assigns a special symbol (e.g., UNK) to the corresponding measured ionic current value in step 44, indicating that no reference change signal CIC(tᵢ; refm(n); meas) is sufficiently similar to the measured ionic current change signal. If the answer to the query in step 43 is "no" (SC is non-empty), the system identifies, in step 45, each reference change signal CIC(tᵢ; refm(n); meas) for which the corresponding error satisfies

\[ e(n)\leq e(\text{thr}) \]

In step 46, the system identifies at least one reference polymer component, for which the corresponding reference change signal CIC(tᵢ; refm(n); meas) is in the surviving collection SC, with the unknown polymer component whose signal was measured.

FIG. 5 is a flow chart of an alternate procedure for practicing the invention, using a transverse voltage difference. In step 51 of FIG. 5, a pipette, having a longitudinal axis and having a tapered tip with an associated pore having a selected pore minimum inner diameter d in a preferred range (e.g., d=1-40 nm) is provided, where a selected self-assembling monolayer is optionally provided on an interior surface of the pore. In step 52, the pore interior is provided with a selected self-assembling monolayer (SAM) is optionally provided on an interior surface of the pore.

The comparison procedure can be summarized in a flow chart in FIG. 6. In step 61, the error \( e(n) \), defined as in Eq. (1) or in another suitable manner, for each reference change signal CIC(tᵢ; refm(n); meas) in the database is computed. In step 62, the surviving collection SC of reference signals is determined. In step 63, the system determines if SC is an empty set. If the answer to the query in step 63 is "yes," the system assigns a special symbol (e.g., UNK) to the corresponding measured ionic current value in step 64, indicating that no reference change signal CIC(tᵢ; refm(n); meas) is sufficiently similar to the measured ionic current change signal. If the answer to the query in step 63 is "no" (SC is non-empty), the system identifies, in step 65, each reference change signal CIC(tᵢ; refm(n); meas) for which the corresponding error satisfies
compounds (e.g., NH₄, N(CH₃)₄), or a suitable ionic organic compound or ionic inorganic compound (e.g., CaSO₄, Mg₆(PO₄)₄), so that the first liquid is present within the pore. More generally, the selected liquid may be any liquid that provides at least a concentration of at least one of a threshold value, for example, p(ton; thr), for each of the following:

In step 53, a voltage difference having a value in a range ΔV=10–2000 milliVolts, or more if desired, is impressed on the first liquid in the pore, in a direction substantially transverse to the pipette longitudinal axis. In step 54, a polymer sequence (unknown) is sequentially passed through the pore, and each of a sequence of electron current change signals is measured, resulting in a sequence of measured values such as the sequences shown in FIG. 2B or FIG. 2C. The electron signals resulting from imposition of the transverse voltage difference are likely to be different from the corresponding 

In step 55 (optional), a sequence of measured electron current change signals CEC(t; meas) is compared, one-by-one or in groups (e.g., with reference change signals CEC(t; ref; n), numbered as in a sequence of reference signals CEC(N; ref; n) in a reference signal database. In step 56 (optional), each polymer unit (e.g., a nucleotide containing a particular base) in the unknown sequence is assigned to the reference polymer component having a reference electron current value that is most similar to the measured electron current signal. Step 55 may, for example, be implemented by analog or implementation of step 35 in FIG. 3, with electronic change signals, CEC(t; meas) and CEC(t; ref; n) replacing the corresponding ion current change signals in Eqs. (1) and (2). The voltage difference amplitude AV(t), impressed longitudinally or transversely across the selected liquid, may be substantially uniform in time, as illustrated in FIG. 6A, may be substantially monotonically increasing in time (FIG. 6B), may be substantially monotonically decreasing in time (FIG. 6C), may be substantially unimodal in time (FIG. 6D), may vary substantially sinuosity in time (FIG. 6E), may vary substantially trapezoidal in time (FIG. 6F), may vary substantially monotonically in time (FIG. 6G), may vary substantially monotonically in time (FIG. 6H). The voltage difference variation shown in FIG. 6I includes a triangular variation, in which the middle segment has length x=0.

A tip region of a pipette (quartz glass, aluminosilicate glass, borosilicate glass or other suitable glass) having an appropriate minimum inner diameter may be formed using the following procedure, illustrated in FIGS. 7A and 7B. A selected middle region 73, having a preferred length LH in a range of 0.1–2 cm, or more, of a pipette 71 with a hollow core is heated or otherwise receives substantial thermal energy, using a laser, infrared source or a heated metal filament 75, and (optional) an associated focusing system 76, at one or more locations, e.g., x=0, x=0, etc., for one, two or more time intervals, of length Δt1, Δt2, etc. The time intervals may partly or wholly overlap or may be isolated from each other. Thus, the heating or irradiation continues, one or both of first and second ends, 77-1 and 77-2, of the pipette is pulled with a selected force F, optionally 10⁻¹–10⁻¹ dynes or more, or at a selected displacement rate, v₀ of a few μm/sec, so that the first and second ends are displaced relative to each other. The pipette 71 separates into two pipette segments, 71-1 and 71-2, in the heating cycle, and at least one of the two resulting pipette segments has a hollow core (a pore) with a pore minimum inner diameter d(min). Tip parameters (thickness, nanopore diameter, nanopore length, etc.) can be partly controlled by appropriate choice of one or more of the parameters heating rate, LH, Δt(irr), F, and/or v.

Suitable applications of the invention, using ion current or electronic current, include the following: (1) counting of genomic or non-genomic fragments, by identification of a first end and/or a second end of each fragment that passes through a nanopore; (2) identification of locations of single strand segments and double strand segments in a "mixed" DNA sequence passing through a nanopore; (3) discrimination between single strands and double strands of DNA passing through a nanopore; and (4) identification of individual nucleotides in single strand DNA passing through a nanopore.

What is claimed is:
1. A method of fabricating a nanopore, the method comprising:
   - heating a hollow cylinder of a pipette material, comprising primarily at least one of quartz glass, aluminosilicate glass and borosilicate glass, by a process comprising using at least one of a laser, an infrared light source and a heated metal for heating one or more locations on the cylinder for a first time interval, the hollow cylinder having first and second cylinder ends, having a longitudinal axis and having a non-zero initial inner diameter; and
   - applying a machine controlled translation force to translate at least one of the first and second cylinder ends relative to the other of the first and second cylinder ends by a change in end-to-end separation distance no greater than about 2 cm during a second time interval that partly or wholly overlaps the first time interval, in order to encourage the hollow cylinder to separate into at least first and second pipettes, each with a corresponding nanopore, with at least one pore diameter in a range of 1–40 nanometers (nm) and with at least one pore length no greater than about 2 cm.
2. The method of 1, further comprising choosing said heating source from a group of heating sources consisting of a laser, an infrared light source, and a heated metal.
3. The method of claim 1, further comprising:
   - providing a selected liquid in contact with an interior surface of said pore;
   - impressing a non-zero voltage difference across the selected liquid within said pore approximately parallel to a longitudinal axis direction of said cylinder, and determining at least one of an electrical current value and an ionic current value induced in the selected liquid; and
   - passing a polymer molecule, having a sequence of polymer components, through said pore in a first direction, determined with reference to the longitudinal axis direction, and determining at least one of an electrical current signal and an ionic current signal induced by passage of each of the polymer components through said pore.
4. The method of claim 3, further comprising selecting material for said pipette from a group of materials including quartz glass, aluminosilicate glass and borosilicate glass.
5. The method of claim 3, further comprising passing said polymer sequence through said pore at an average rate in a range of 1–1000 polymer components per second.
6. The method of claim 3, further comprising choosing said polymer sequence to be a nucleic acid sequence including the bases adenine, cytosine and guanine and at least one of the bases thymine and uracil.
7. The method of claim 3, further comprising selecting said voltage difference from a group of time-dependent differences including a difference that (i) is approximately uniform in time; (ii) increases monotonically with time; (iii) decreases monotonically with time; (iv) is a step function in time; (v) varies sinusoidally with time; and (vi) varies trapezoidally with time.

8. The method of claim 3, further comprising choosing said selected liquid to include at least one of an alkali halide, an ammonium compound, an ionic organic compound and an ionic inorganic compound.

9. The method of claim 1, further comprising providing a self-assembling monolayer of a selected substance on a selected portion of said interior surface of said pore.

10. The method of claim 9, further comprising choosing said self assembling monolayer to include at least one of: (i) octadecyltrichlorosilane on glass and (ii) (16-Mercapto)hexadecanoic acid on a gold substrate.

11. The method of claim 1, further comprising: providing a selected liquid in contact with an interior surface of said pore; impressing a non-zero voltage difference across the selected liquid within said pore transverse to a longitudinal axis direction of said cylinder, and determining an ionic current value induced in the selected liquid; and passing a polymer molecule, having a sequence of polymer components, through said pore in a first direction, determined with reference to the longitudinal axis direction, and determining an ionic current signal induced by passage of each of the polymer components through said pore.

12. The method of claim 11, further comprising passing said polymer sequence through said pore at an average rate in a range of 1-1000 polymer components per msec.

13. The method of claim 11, further comprising choosing said polymer sequence to be a nucleic acid sequence including the bases adenine, cytosine and guanine and at least one of the bases thymine and uracil.

14. The method of claim 11, further comprising selecting said voltage difference from a group of time-dependent differences including a difference that (i) is substantially uniform in time; (ii) increases monotonically with time; (iii) decreases monotonically with time; (iv) is a step function in time; (v) varies sinusoidally with time; and (vi) varies trapezoidally with time.

15. The method of claim 11, further comprising choosing said selected liquid to include at least one of an alkali halide, an ammonium compound, an ionic organic compound and an ionic inorganic compound.

16. The method of claim 1, further comprising providing a self-assembling monolayer of a selected substance on a portion of said interior surface of said pore.

17. The method of claim 16, further comprising choosing said self assembling monolayer to include at least one of: (i) octadecyltrichlorosilane on glass and (ii) (16-Mercapto)hexadecanoic acid on a gold substrate.

18. The method of claim 1, further comprising applying said machine controlled translation force in a range of between 10 dynes and 10 million dynes in a direction corresponding to said longitudinal axis.

* * * * *