Directing Motion of Droplets Using Differential Wetting

BACKGROUND

[0001] This application claims from United States provisional App. Ser. No. 62/811,018, filed February 27, 2019, titled Directing Motion of Droplets Using Differential Wetting, and United States provisional App. Ser. No. 62/636,268, filed Feb. 28, 2018, titled Manufacturing Methods for Electrowetting Microfluidic Chip. These applications are incorporated by reference.

[0002] This application relates to controlling and manipulating a liquid or gas in a device that is small, typically milliliter to sub-microliter scale.

SUMMARY

[0002a] In an aspect, the present disclosure refers to a system for processing a sample, comprising: an array comprising (i) a first plurality of electrodes, (ii) a second plurality of electrodes, (iii) a liquid coating filling in gaps between adjacent electrodes of said first plurality of electrodes and said second plurality of electrodes, (iv) a dielectric disposed over said first plurality of electrodes, said second plurality of electrodes, and said liquid coating filling in gaps between said adjacent electrodes, and (v) a liquid layer disposed over said dielectric, wherein said liquid layer is configured to support a droplet on a surface of said liquid layer, wherein said droplet comprises said sample, wherein said liquid layer comprises a liquid that has a wetting affinity characteristic for said dielectric, wherein said liquid is immiscible with said droplet, and wherein said first plurality of electrodes and said second plurality of electrodes are configured to supply an electric field to induce said droplet to motion along a surface of said liquid layer; and a controller operatively coupled to said first plurality of electrodes and said second plurality of electrodes, wherein said controller is configured to direct at least a subset of said first plurality of electrodes and said second plurality of electrodes to supply said electric field to alter a wetting characteristic of said surface of said liquid layer, to thereby induce said droplet to motion along said surface of said liquid layer.

[0002b] In another aspect, the present disclosure refers to a method for processing a sample, comprising: (a) providing an array comprising: (i) a first plurality of electrodes, (ii) a second plurality of electrodes, (iii) a liquid coating filling in gaps between adjacent electrodes of said first plurality of electrodes and said second plurality of electrodes, (iv) a dielectric disposed over said first plurality of electrodes, said second plurality of electrodes, and said liquid coating filling in gaps between said adjacent electrodes, and (v) a liquid layer disposed over said dielectric, wherein said liquid layer is configured to support a droplet on a surface of said liquid layer, wherein said droplet comprises said sample, wherein said liquid layer comprises a liquid that has a wetting affinity characteristic for said dielectric, and wherein said liquid is immiscible with said droplet; (b)

introducing said droplet comprising said sample on said surface of said liquid layer disposed over said dielectric; and (c) directing at least a subset of said first plurality of electrodes and said second plurality of electrodes to supply an electric field to alter a wetting characteristic of said surface of said liquid layer, to thereby induce said droplet to motion along said surface of said liquid layer.

[0003] In general, in a first ~~aspect~~example, the ~~invention~~ present disclosure features apparatus for controlling motion of liquid droplets. A set of electrode pads is arranged in an array or in paths defining one or more tracks over which liquid droplets may be induced to move over a sequence of the electrode pads. A surface over the electrode pads is dielectric, smooth to within 2μm, has a slide angle for a 5μl droplet of the liquid of no more than 5 degrees, and has a wetting affinity to the liquid that can be altered by application of voltage to the electrode pads. A control is designed to alter the wetting characteristic of portions of the surface over respective electrode pads to effect induced motion of the droplets over the tracks, the wetting characteristic to be altered by controlling charging and discharging of the electrode pads in a desired sequence.

[0004] In general, in a second ~~aspect~~example, the present disclosure ~~invention~~ features apparatus for controlling motion of liquid droplets. A smooth, hydrophobic surface has portions with a wetting affinity to the liquid that can be varied in a controlled manner. The varying-wettability portions are arranged in an array or in paths defining one or more tracks over which liquid droplets may be induced to move over a sequence of the varying-wettability portions. A control is designed to vary the wetting characteristic of varying-wettability portions of the surface to effect induced motion of the droplets over the tracks. The apparatus is designed with the smooth hydrophobic surface open, with no overlying or facing electrode or plate above the droplets.

[0005] In general, in a third ~~aspect~~example, the present disclosure ~~invention~~ features apparatus for controlling motion of liquid droplets. A solid surface is textured to hold a thin layer of a second liquid that is immiscible with the liquid of the droplets, an upper surface of the second liquid forming a liquid-liquid surface that is slippery with respect to the liquid droplets, having a slide angle for a 5μl droplet of the droplet liquid of no more than 5 degrees, and having a wetting affinity to the droplet liquid that can be varied under control, the varying-wettability portions being arranged in an array or in paths defining one or more tracks over which the liquid droplets may be induced to move over a sequence of the varying-wettability portions. A control is designed to vary the wetting characteristic of varying-wettability portions of the liquid-liquid surface to effect induced motion of the droplets over the tracks.

[0006] In general, in a fourth ~~aspect~~example, the present disclosure ~~invention~~ features apparatus for controlling motion of liquid droplets. A set of electrode pads is arranged in an array or in paths defining one or more tracks over which liquid droplets may be induced to move over a sequence of the electrode pads. A surface over the electrode pads is dielectric, smooth to within 1µm, the smooth surface being formed as a thin layer of a second liquid that is immiscible with the liquid of the droplets, an upper surface of the second liquid forming a liquid-liquid surface that is hydrophobic, having a slide angle for a 5µl droplet of the liquid of no more than 5 degrees, and having portions whose wetting affinity to the liquid that can be individually varied in a controlled manner by application of voltage to respective electrode pads, the varying-wettability portions being arranged in an array or in paths defining one or more tracks over which liquid droplets may be induced to move over a sequence of the varying-wettability portions. The second liquid is laid as a thin layer on a surface of an underlying solid substrate that is textured to hold the second liquid stable against gravity. A control is designed to alter the wetting characteristic of varying-wettability portions of the surface over respective electrode pads to effect induced motion of the droplets over the tracks, the wetting characteristic to be altered by controlling charging and discharging of the electrode pads in a desired sequence. The apparatus is designed with the smooth hydrophobic surface open, with no overlying or facing electrode or plate above the droplets.

[0007] In general, in a fifth ~~aspect~~example, the present disclosure ~~invention~~ features a method. A liquid droplet is introduced onto a surface over a set of electrode pads arranged in an array or in paths defining one or more tracks over which the liquid droplet may be induced to move over a sequence of the electrode pads. The surface is dielectric, hydrophobic, smooth to within 2µm, and has a slide angle for a 5µl droplet of the liquid of no more than 5 degrees, and has a wetting affinity to the liquid that can be altered by application of voltage to the electrode pads. The varying-wettability portions are arranged in an array or in paths defining one or more tracks over which liquid droplets may be induced to move over a sequence of the varying-wettability portions. The wetting characteristic of portions of the surface over respective electrode pads is controlled to effect induced motion of the droplet over the tracks, the wetting characteristic to be altered by controlling charging and discharging of the electrode pads in a desired sequence. The surface is designed with the smooth hydrophobic surface open, with no overlying or facing electrode or plate above the droplets.

[0008] ~~Embodiments~~ Examples of the present disclosure ~~invention~~ may include one or more of the following features. The motive voltage may be less than 100V, less than 80V, less than 50V, less than 40V, less than 30V, or less than 20V. The electrodes may be printed on a substrate using printed circuit board technology, or manufactured using thin-film transistor (TFT), active matrix, or passive matrix backplane technology. Various levels of smoothing may be preferred, from 5µm, 2µm, 1µm, 500nm, 200nm, or 100nm. The surface may be smoothed to within 1µm by polishing. The surface may be smoothed to within 1µm by applying a coating, the coating applied by at least one of spin coating, spray coating, dip coating, or vapor deposition. The surface coating may be of a material that is both dielectric and hydrophobic. The surface may be smoothed to within 1µm by application of a sheet of a polymer stretched to remove wrinkles. The slide angle may be imparted to the surface by patterning or texturing to induce hydrophobicity. The slide angle of a 5µl droplet may be no more than 5º, 3º, 2º, or 1º. A set of

CLAIMS

~~The invention claimed is:~~

1. ~~1. Apparatus~~A system for ~~controlling motion of liquid droplets~~processing a sample, comprising:

~~a set of electrode pads arranged in an array or in paths defining one or more tracks over which liquid droplets may be induced to move over a sequence of the electrode pads;~~
~~a surface over the electrode pads being dielectric, smooth to within 2μm, having a slide angle for a 5μl droplet of the liquid of no more than 5 degrees, and having a wetting affinity to the liquid that can be altered by application of voltage to the electrode pads;~~
~~a control designed to alter the wetting characteristic of portions of the surface over respective electrode pads to effect induced motion of the droplets over the tracks, the wetting characteristic to be altered by controlling charging and discharging of the electrode pads in a desired sequence.~~

~~2. Apparatus for controlling motion of liquid droplets, comprising:~~
~~a smooth, hydrophobic surface, having portions with a wetting affinity to the liquid that can be varied in a controlled manner to induce droplets of the liquid to move over the surface;~~
~~a control designed to vary the wetting characteristic of portions of the surface to effect induced motion of the droplets over the tracks;~~
~~the apparatus being designed with the smooth hydrophobic surface open, with no overlying or facing electrode or plate above the droplets.~~

~~3. The apparatus of any of claims 1 or 2:~~
~~the smooth surface being hydrophobic;~~
~~the smooth hydrophobic surface being formed as a textured surface of a solid, designed to hold a thin layer of a second liquid that is immiscible with the liquid of the droplets, an upper surface of the second liquid forming a liquid-liquid surface that is slippery with respect to the liquid droplets.~~

~~4. Apparatus for controlling motion of liquid droplets, comprising:~~
~~a solid surface that is textured to hold a thin layer of a second liquid that is immiscible with the liquid of the droplets, an upper surface of the second liquid forming a liquid-liquid surface that is slippery with respect to the liquid droplets, having a slide angle for a 5μl droplet of the droplet liquid of no more than 5 degrees, and having a wetting affinity to the droplet liquid that can be varied under control, the varying-wetability portions being arranged in an array or in paths defining one or more tracks over which the liquid droplets may be induced to move over a sequence of the varying-wetability portions; and~~
~~a control designed to vary the wetting characteristic of varying-wetability portions of the liquid-liquid surface to effect induced motion of the droplets over the tracks.~~

~~5. The apparatus of claim 4, wherein:~~
~~the second liquid is an oil that has wetting affinity for the solid and is immiscible with the liquid of the droplets.~~

6. The apparatus of any of claims 2, 4, or 5, further comprising:
the varying-wetability portions being a surface arranged over a set of electrode pads arranged in an array or in paths defining one or more tracks over which liquid droplets may be induced to move over a sequence of the electrode pads, the varying-wetability portions being a dielectric surface over the electrode pads, the wetting characteristic to be altered by controlling charging and discharging of the electrode pads in a desired sequence.

7. The apparatus of claims 2, 4, 5, or 6:
the smooth, hydrophobic surface is smooth to within 1μm, and has a slide angle for a 5μl droplet of the liquid of no more than 5 degrees.

8. The apparatus of any of claims 1, 4, 5, 6, or 7 :
the smooth surface being hydrophobic;
the apparatus being designed with the smooth hydrophobic surface being open, with no overlying or facing electrode or plate.

9. The apparatus of any of claims 1, 4, 5, 6, 7, or 8, further comprising:
a second plate overlying or facing the surface.

10. The apparatus of any of claims 1, 6, 7, or 8, wherein:
the electrodes are printed on a substrate using printed circuit board technology.

11. The apparatus of any of claims 1, 6, 7, or 8, wherein:
the electrodes are manufactured using thin-film transistor (TFT) technology.

12. The apparatus of any of claims 1, 6, or 7, or 8, wherein:
the electrodes are manufactured on a substrate using active matrix or passive matrix backplane technology.

13. The apparatus of any of claims 1, 4 to 8, and 9 to 12, wherein:
the slide angle is imparted to the surface by patterning or texturing to induce hydrophobicity.

14. The apparatus of any of the preceding claims, wherein:
the surface has a slide angle for a 5μl droplet of no more than 3º.

15. The apparatus of any of the preceding claims, wherein:
the surface has a slide angle for a 5μl droplet of no more than 1º.

16. The apparatus of any of the preceding claims, wherein:
the wetability of the varying-wetability portions of the surface is varied via application of light.

17. The apparatus of any of the preceding claims, wherein:
the varying-wetability portions of the surface operate by optoelectrowetting.

~~18. The apparatus of any of the preceding claims 1 to 17, wherein, wherein:~~
~~the varying wetability portions of the surface operate by photoelectrowetting.~~

~~19. The apparatus of any of the preceding claims, wherein:~~
~~the surface is smoothed to within 1μm by polishing.~~

~~20. The apparatus of any of the preceding claims, wherein:~~
~~the surface is smoothed to within 1μm by applying a coating, the coating applied by at least one of spin coating, spray coating, dip coating, or vapor deposition.~~

~~21. The apparatus of any of the preceding claims, wherein:~~
~~the surface coating is of a material that is both dielectric and hydrophobic.~~

~~22.~~ an array comprising (i) a first plurality of electrodes, (ii) a second plurality of electrodes, (iii) a liquid coating filling in gaps between adjacent electrodes of said first plurality of electrodes and said second plurality of electrodes, (iv) a dielectric disposed over said first plurality of electrodes, said second plurality of electrodes, and said liquid coating filling in gaps between said adjacent electrodes, and (v) a liquid layer disposed over said dielectric, wherein said liquid layer is configured to support a droplet on a surface of said liquid layer, wherein said droplet comprises said sample, wherein said liquid layer comprises a liquid that has a wetting affinity characteristic for said dielectric, wherein said liquid is immiscible with said droplet, and wherein said first plurality of electrodes and said second plurality of electrodes are configured to supply an electric field to induce said droplet to motion along a surface of said liquid layer; and

a controller operatively coupled to said first plurality of electrodes and said second plurality of electrodes, wherein said controller is configured to direct at least a subset of said first plurality of electrodes and said second plurality of electrodes to supply said electric field to alter a wetting characteristic of said surface of said liquid layer, to thereby induce said droplet to motion along said surface of said liquid layer.

2. The system of claim 1, wherein said electric field is between a subset of electrodes of said first plurality of electrodes, a subset of electrodes of said second plurality of electrodes, or between said first plurality of electrodes and said second plurality of electrodes.

3. The system of claim 1, wherein said second plurality of electrodes has a thickness of less than 10 μm.

4. The system of claim 1, wherein said surface of said liquid layer comprises one or more paths, wherein a path of said one or more paths comprises one or more tracks for motion of said droplet.

5. The system of claim 1, wherein said surface of said liquid layer is configured to support an additional droplet comprising an additional sample or a chemical sample.

6. The system of claim 1, further comprising a light source operatively coupled to said controller, wherein said controller is configured to alter said wetting characteristic of said surface of said liquid layer by directing said light source to apply light to said array.

7. The system of claim 1, further comprising one or more dispensers configured to dispense or remove said droplet to or from said surface.

8. The system of claim 1, wherein said dielectric comprises a polymeric material.

9. The system of claim 8, wherein said polymeric material is removable.

10. The system of claim 1, wherein said first plurality of electrodes and said second plurality of electrodes are coplanar.

11. The system of claim 1, wherein said first plurality of electrodes and said second plurality of electrodes are non-coplanar.

12. The system of claim 1, wherein said array further comprises one or more stations, wherein said one or more stations are selected from the group consisting of a mixing station, a temperature control station, a magnetic field station, an acoustic field station, a nucleic acid delivery station, an optical inspection station, an optical manipulation station, a droplet input station and a droplet output station.

13. The system of claim 1, wherein said dielectric has a thickness of at least 25 nanometers or at most 100 μm.

14. The system of claim 1, wherein said liquid layer comprises an upper surface, and wherein said upper surface of said liquid layer, said droplet, and a gas form a liquid-liquid-gas interface.

15. The system of claim 1, wherein said liquid layer and said dielectric form an electrical barrier between (1) said first plurality of electrodes and said second plurality of electrodes, and (2) said droplet.

16. The system of claim 1, wherein said liquid coating comprises a photoresist, epoxy, potting compound, liquid polymer, or other dielectric.

17. The system of claim 1, wherein said droplet comprises a biological sample.

18. The system of claim 1, wherein said electric field induces said droplet to motion in at least two directions along said surface of said liquid layer.

19. A method for processing a sample, comprising:

(a) providing an array comprising: (i) a first plurality of electrodes, (ii) a second plurality of electrodes, (iii) a liquid coating filling in gaps between adjacent electrodes of said first plurality of electrodes and said second plurality of electrodes, (iv) a dielectric disposed over said first plurality of electrodes, said second plurality of electrodes, and said liquid coating filling in gaps between said adjacent electrodes, and (v) a liquid layer disposed over said dielectric, wherein said liquid layer is configured to support a droplet on a surface of said liquid layer, wherein said droplet comprises said sample, wherein said liquid layer comprises a liquid that has a wetting affinity characteristic for said dielectric, and wherein said liquid is immiscible with said droplet;

(b) introducing said droplet comprising said sample on said surface of said liquid layer disposed over said dielectric; and

(c) directing at least a subset of said first plurality of electrodes and said second plurality of electrodes to supply an electric field to alter a wetting characteristic of said surface of said liquid layer, to thereby induce said droplet to motion along said surface of said liquid layer.

20. The method of claim 19, wherein altering said wetting characteristic comprises controlling charging and discharging of one or more electrodes of said first plurality of electrodes and said second plurality of electrodes in sequence.

21. The method of claim 19, wherein altering said wetting characteristic comprises applying light to said array.

The ~~apparatus~~method of ~~any of the preceding claims, wherein:~~

~~the surface is smoothed to within 1µm by application of a sheet of a polymer stretched to remove wrinkles.~~

~~23. The apparatus of any of the preceding claims~~claim 19, further comprising~~:~~

~~the apparatus includes stations for one~~, during or ~~more of the group consisting of dispensing, mixing,~~subsequent to (b), subjecting said droplet to heating, cooling, ~~application of magnetic field, application of electric field, addition of reagent, optical inspection or assay, and isolation or purification of proteins, peptides, or biopolymers.~~

~~24. The apparatus of any of the preceding claims, further comprising:~~

~~2.~~22. ~~the apparatus includes stations for two or more of the group consisting of dispensing, mixing, heating, cooling, application of~~a magnetic field, ~~application of electric field, addition of reagent, optical inspection or assay, and isolation or purification of proteins, peptides, or biopolymers~~a light field, acoustic energy, or mixing to manipulate said sample.

23. ~~25.~~ The ~~apparatus~~method of ~~any~~claim 19, wherein said sample comprises a nucleic acid or a protein, and wherein subsequent to (c), said nucleic acid or protein is processed within said droplet.

The method of ~~the preceding claims~~claim 19, further comprising~~:~~

~~an acoustic transducer configured to introduce~~, during or subsequent to ~~introduce liquid droplets into the apparatus.~~

~~26. The apparatus of any of the preceding claims, further~~(b), introducing an additional droplet comprising~~:~~

~~a microdiaphragm pump configured to introduce to introduce liquid droplets into the apparatus.~~

~~27. The apparatus of any of the preceding claims, further comprising:~~

~~3.~~24. ~~one or more inkjet nozzles configured to introduce liquid droplets into the apparatus~~additional samples over said surface.

~~28. The apparatus of any of the preceding claims, further comprising:~~
~~one or more syringe pumps configured to introduce liquid droplets into the apparatus.~~

~~4.~~25. ~~29. The apparatus of any of the preceding claims~~The method of claim 24, further comprising~~:~~ merging said droplet and said additional droplet.

~~one or more capillary tubes configured to introduce liquid droplets into the apparatus.~~

~~5.~~26. ~~30. The apparatus~~method of ~~any of the preceding claims~~claim 19, further comprising~~:~~ splitting said droplet.

~~one or more pipette devices configured to introduce liquid droplets into the apparatus.~~

~~6.~~27. ~~31. The apparatus~~method of ~~any of the preceding claims~~claim 19, further comprising~~:~~ replenishing said liquid layer.

~~the surface has one or more holes designed to introduce liquid droplets or reactants.~~

~~32. A method, comprising the steps of:~~
~~introducing a liquid droplet onto a surface over a set of electrode pads arranged in an array or in paths defining one or more tracks over which the liquid droplet may be induced to move over a sequence of the electrode pads;~~
~~the surface being dielectric, smooth to within 2µm, having a slide angle for a 5µl droplet of the liquid of no more than 5 degrees, and having a wetting affinity to the liquid that can be altered by application of voltage to the electrode pads;~~
~~controlling the wetting characteristic of portions of the surface over respective electrode pads to effect induced motion of the droplet over the tracks, the wetting characteristic to be altered by controlling charging and discharging of the electrode pads in a desired sequence.~~

~~33. A method, comprising the step of:~~
~~introducing a liquid droplet onto a smooth, hydrophobic surface, having portions with a wetting affinity to the liquid that can be varied in a controlled manner, the varying wettability portions being arranged in an array or in paths defining one or more tracks over which liquid droplets may be induced to move over a sequence of the varying wettability portions;~~
~~varying the wetting characteristic of varying wettability portions of the surface to effect induced motion of the droplets over the tracks;~~
~~the apparatus being designed with the smooth hydrophobic surface open, with no overlying or facing electrode or plate above the droplets.~~

~~34. The method of any of claims 32 and 33:~~

~~the surface being hydrophobic, and~~

~~the smooth, hydrophobic surface being formed as a textured surface of a solid, designed to hold a thin layer of a second liquid that is immiscible with the liquid of the droplets, an upper surface of the second liquid forming a liquid-liquid surface that is slippery with respect to the liquid droplets.~~

~~35. A method, comprising the step of:~~

~~introducing a liquid droplet onto a liquid-liquid interface, being a liquid surface of a second liquid that is immiscible with the liquid of the droplets, formed on a solid surface that is textured to hold a thin layer of the second liquid, an upper surface of the second liquid forming a liquid-liquid surface that is slippery with respect to the liquid droplets, having a slide angle for a 5µl droplet of the droplet liquid of no more than 5 degrees, and having a wetting affinity to the droplet liquid that can be varied under control, the varying-wettability portions being arranged in an array or in paths defining one or more tracks over which the liquid droplets may be induced to move over a sequence of the varying-wettability portions; and~~

~~varying the wetting characteristic of varying-wettability portions of the liquid-liquid surface to effect induced motion of the droplets over the tracks.~~

~~36. The method of any of claims 33, 34, or 35:~~

~~the varying-wetability portions being a surface arranged over a set of electrode pads arranged in an array or in paths defining one or more tracks over which liquid droplets may be induced to move over a sequence of the electrode pads, the varying-wetability portions being a dielectric surface over the electrode.~~

~~pads, the wetting characteristic to be altered by controlling charging and discharging of the electrode pads in a desired sequence.~~

~~37. The method of any of claims 33, 34, 35, or 36:~~

~~the smooth, hydrophobic surface being smooth to within 1µm, and having a slide angle for a 5µl droplet of the liquid of no more than 3 degrees.~~

~~38. The method of any of claims 32, and 35 to 37:~~

~~the apparatus being designed with the smooth hydrophobic surface open, with no overlying or facing electrode or plate above the droplets.~~

~~7.~~28. ~~39.~~ The method of claim ~~32, 36, or 37~~19, wherein~~:~~ said dielectric comprises a polymeric material.

~~the electrodes are printed on a substrate using printed circuit board technology.~~

~~40.~~ The method of ~~any of the preceding claims 42 to 39~~claim 19, wherein~~:~~

~~the surface is smoothed to within 1µm by polishing.~~

~~41. Apparatus for controlling motion of~~ said liquid ~~droplets, comprising:~~

~~a set of electrode pads arranged in an array or in paths defining one or more tracks over which liquid droplets may be induced to move over a sequence of the electrode pads;~~

~~8.~~29. ~~a surface over the electrode pads being~~layer and said dielectric~~, smooth to within 1μm, the smooth surface being formed as a thin layer of a~~ form an electrical barrier between (1) said first plurality of electrodes and said second ~~liquid that is immiscible with the liquid of the droplets, an upper surface of the second liquid forming a liquid-liquid surface that is hydrophobic, having a slide angle for a 5μl~~plurality of electrodes, and (2) said droplet ~~of the liquid of no more than 5 degrees, and having portions whose wetting affinity to the liquid that can be individually varied in a controlled manner by application of voltage to respective electrode pads, the varying-wetability portions being arranged in an array or in paths defining one or more tracks over which liquid droplets may be induced to move over a sequence of the varying-wetability portions, the second liquid laid on a surface of an underlying solid substrate that is textured to hold the second liquid stable against gravity;~~.

~~a control designed to alter the wetting characteristic of varying-wetability portions of the surface over respective electrode pads to effect induced motion of the droplets over the tracks, the wetting characteristic to be altered by controlling charging and discharging of the electrode pads in a desired sequence;~~

~~the apparatus being designed with the smooth hydrophobic surface open, with no overlying or facing electrode or plate above the droplets.~~

~~9.~~30. The method of claim 19, wherein said liquid coating comprises a photoresist, epoxy, potting compound, liquid polymer, or other dielectric.