

## LENS WITH MULTI-SEGMENTED LINEAR MENISCUS WALL

### FIELD OF USE

5           The present invention relates generally to a liquid meniscus lens, more specifically, it includes an arcuate liquid meniscus lens with a meniscus wall including multiple conical frustum segments.

### BACKGROUND

10           Liquid meniscus lenses have been known in various industries. As discussed more fully below with reference to Figs. 1A and 1B, known liquid meniscus lenses were engineered in cylindrical shapes with a perimeter surface formed by points at a fixed distance from an axis which is a straight line. Known liquid meniscus lenses have been limited to designs with a first interior surface generally parallel to second interior surface and each perpendicular to a cylindrical axis. Known examples of the use of liquid meniscus  
15           lenses include devices such as electronic cameras and mobile phone devices.

            Traditionally, an ophthalmic device, such as a contact lens and an intraocular lens included a biocompatible device with a corrective, cosmetic or therapeutic quality. A contact lens, for example, can provide one or more of: vision correcting functionality;

cosmetic enhancement; and therapeutic effects. Each function is provided by a physical characteristic of the lens. A design incorporating a refractive quality into a lens can provide a vision corrective function. A pigment incorporated into the lens can provide a cosmetic enhancement. An active agent incorporated into a lens can provide a therapeutic  
5 functionality.

More recently, electronic components have been incorporated into a contact lens. Some components can include semiconductor devices. However, physical constraints including the size, shape and control aspects of a liquid meniscus lens have precluded their use in an ophthalmic lens. Generally the cylindrical shape, sometimes referred to as the  
10 "hockey puck" shape of liquid meniscus lenses, has not been conducive to something that can work in a human eye.

In addition, a curved liquid meniscus lens includes physical challenges that are not necessarily present in a traditional design of a liquid meniscus lens with parallel sidewalls.

#### SUMMARY

15 Accordingly, the present invention provides a liquid meniscus lens including an arcuate front curve lens and an arcuate back curve lens. Included in the present invention is a meniscus wall with physical features conducive for one or both of attraction and repulsion of a liquid contained within the lens and forming a meniscus with another liquid.

20 According to the present invention, a first arcuate shaped optic is proximate to a second arcuate shaped optic with a cavity formed therebetween. A saline solution and an oil are maintained within the cavity. Application of an electrostatic charge to a meniscus wall generally located in a perimeter area of one or both of the first arcuate optic and the second arcuate optic changes the physical shape of a meniscus formed between the saline solution and oil maintained within the cavity.

25 The present invention includes a meniscus wall formed into a compound shape essentially including multiple linear segments, a cross-section of which includes multiple conical frustum segments in mechanical communication with each other.

## DESCRIPTION OF THE DRAWINGS

Fig. 1A illustrates a prior art example of a cylindrical liquid meniscus lens in a first state.

5 Fig. 1B illustrates the prior art example of a cylindrical liquid meniscus lens in a second state.

Fig. 2 illustrates a profile sliced cut away of an exemplary liquid meniscus lens according to some embodiments of the present invention.

10 Fig. 3 illustrates a cross section of a portion of an exemplary arcuate liquid meniscus lens, according to some embodiments of the present invention.

Fig. 4 illustrates additional exemplary aspects of an arcuate liquid meniscus lens.

Fig. 5 illustrates meniscus wall elements within an arcuate liquid meniscus lens, according to some embodiments of the present invention.

15 Fig. 6A illustrates a multi-step meniscus wall within a liquid meniscus lens, showing a liquid meniscus boundary in an unpowered state, according to some embodiments of the present invention.

Fig. 6B illustrates a multi-step meniscus wall within a liquid meniscus lens, showing a liquid meniscus boundary in a powered state, according to some embodiments of the present invention.

20 Fig. 6C illustrates a multi-step meniscus wall within a liquid meniscus lens, showing a powered and an unpowered state of a liquid meniscus boundary in a single diagram for comparison.

25 Fig. 7A illustrates a multi-gradient meniscus wall within a liquid meniscus lens, showing a liquid meniscus boundary in an unpowered state, according to some embodiments of the present invention.

Fig. 7B illustrates a multi-gradient meniscus wall within a liquid meniscus lens, showing a liquid meniscus boundary in a powered state, according to some embodiments of the present invention.

Fig. 7C illustrates a multi-gradient meniscus wall within a liquid meniscus lens, showing a powered and an unpowered state of a liquid meniscus boundary in a single diagram for comparison.

Fig. 8A illustrates a cross-section of a multi-step meniscus wall viewed separately from the rest of an arcuate liquid meniscus lens, according to some embodiments of the present invention.

Fig. 8B illustrates a cross-section of a multi-gradient meniscus wall viewed separately from the rest of an arcuate liquid meniscus lens, according to some embodiments of the present invention.

Fig. 8C illustrates a cross-section of a frustum of a cone, which is the shape of one linear segment of a multi-step meniscus wall or one gradient of a multi-gradient meniscus wall when viewed separately from the rest of an arcuate liquid meniscus lens.

#### DETAILED DESCRIPTION OF THE INVENTION

The present invention provides for a liquid meniscus lens with at least one of a front curve lens and a back curve lens defining a meniscus cavity of the liquid meniscus lens.

#### GLOSSARY

In this description and claims directed to the presented invention, various terms may be used for which the following definitions will apply:

20 Contact Angle: The angle at which the oil/saline solution interfacc, also referred to as the liquid meniscus boundary, meets the meniscus wall. In the case of a linear meniscus wall, the contact angle is measured as the angle between the meniscus wall and the line tangent to the liquid meniscus boundary at the point where the liquid meniscus boundary meets the meniscus wall. In the case of a curved meniscus wall, the contact angle is  
25 measured as the angle between the lines tangent to the meniscus wall and the liquid meniscus boundary at the point where they meet.

Lens: As used herein, a Lens means an article with a front surface and a back surface that is optically transmissive to a predefined range of wavelengths of radiation, such

as, by way of example, visible light. A lens may include one or both of a front surface and a back surface which are essentially flat or one or both of a front surface and a back surface which are arcuate in shape.

Liquid Meniscus Boundary: The arcuate surface interface between the saline  
5 solution and the oil. Generally, the surface will form a lens that is concave on one side and convex on the other.

Meniscus Cavity: The space in an arcuate liquid meniscus lens between the front curve lens and the back curve lens in which oil and saline solution are maintained.

Meniscus Wall: A specific area on the interior of the front curve lens, such that it is  
10 within the meniscus cavity, along which the liquid meniscus boundary moves.

Optical Zone: as used herein refers to an area of an ophthalmic lens through which a wearer of the ophthalmic lens sees.

Sharp: A geometric feature of an internal surface of either a front curve or back curve lens piece sufficient to contain the location of a contact line of two predefined fluids  
15 on the optic. The sharp is usually an outside corner rather than an inside corner. From a fluid standpoint it is an angle greater than 180 degrees.

Referring now to Fig. 1A, a cut away view of a prior art lens 100 is illustrated with an oil 101 and a saline solution 102 contained within cylinder 110. The cylinder 110 includes two plates of optical material 106. Each plate 106 includes an essentially flat  
20 interior surface 113-114. The cylinder 110 includes an interior surface that is essentially rotationally symmetric. In some prior art embodiments, one or more surfaces may include a hydrophobic coating. Electrodes 105 are also included on or about the perimeter of the cylinder. An electrical insulator may also be used proximate to the electrodes 105.

According to the prior art, each of the interior surfaces 113-114 is essentially flat or  
25 planar. An interface surface 112A is defined between the saline solution 102A and the oil 101. As illustrated in Fig. 1A, the shape of the interface 112A is combined with the refractive index properties of the saline solution 102A and the oil 101 to receive incident light 108 through a first interior surface 113 and provide divergent light 109 through a second interior surface 114. The shape of the interface surface between the oil 101 and the

saline solution 102 may be altered with the application of an electrical potential to the electrodes 105.

Fig. 100A illustrates a perspective view of the prior art lens illustrated at 100.

Referring now to Fig. 1B, the prior art lens 100 is illustrated in an energized state.

5 The energized state is accomplished by applying voltage 114 across the electrodes 115. The shape of the interface surface 112B between the oil 101 and the saline solution 102B is altered with the application of an electrical potential to the electrodes 115. As illustrated in Fig. 1B, incident light 108B passing through the oil 101 and the saline solution 102B is focused into a convergent light pattern 111.

10 Referring now to Fig. 2, a cut away view of a liquid meniscus lens 200 with a front curve lens 201 and a back curve lens 202. In various embodiments, the front curve lens 201 and the back curve lens 202 may include an arcuate lens or a substantially flat lens. In some preferred embodiments, the front curve lens 201 and the back curve lens 202 are positioned proximate to each other and form a cavity 210 therebetween. The front curve lens 201  
15 includes a concave arcuate interior lens surface 203 and a convex arcuate exterior lens surface 204. The concave arcuate interior lens surface 203 may have one or more coatings (not illustrated in Fig. 2). Coatings may include, for example, one or more of electrically conductive materials or electrically insulating materials, hydrophobic materials or hydrophilic materials. One or both of the concave arcuate interior lens surface 203 and the  
20 coatings are in liquid and optical communication with an oil 208 contained within the cavity 210.

The back curve lens 202 includes a convex arcuate interior lens surface 205 and a concave arcuate exterior lens surface 206. The convex arcuate interior lens surface 205 may have one or more coatings (not illustrated in Fig. 2). Coatings may include, for example,  
25 one or more of electrically conductive materials or electrically insulating materials, hydrophobic materials or hydrophilic materials. At least one of the convex arcuate interior lens surface 205 and the coatings are in liquid and optical communication with a saline solution 207 contained within the cavity 210. The saline solution 207 includes one or more salts or other components which are ionically conductive and as such may be either attracted  
30 to or repulsed by an electric charge.

According to the present invention, an electrically conductive coating 209 is located along at least a portion of a periphery of one or both of the front curve lens 201 and the back curve lens 202. The electrically conductive coating 209 may include gold or silver and is preferably biocompatible. Application of an electrical potential to the electrically  
5 conductive coating 209 creates either an attraction or a repulsion of the ionically conductive salts or other components in the saline solution 207.

The front curve lens 201 has an optical power in relation to light passing through the concave arcuate interior lens surface 203 and a convex arcuate exterior lens surface 204. The optical power may be 0 or may be a plus or minus power. In some preferred  
10 embodiments, the optical power is a power typically found in corrective contact lenses, such as, by way of non-limiting example, a power between -8.0 and +8.0 diopters.

The back curve lens 202 has an optical power in relation to light passing through the convex arcuate interior lens surface 205 and a concave arcuate exterior lens surface 206. The optical power may be 0 or may be a plus or minus power. In some embodiments, the  
15 optical power is a power typically found in corrective contact lenses, such as, by way of non-limiting example, a power between -8.0 and +8.0 diopters. An optical axis 212 is formed through the back curve lens 202 and the front curve lens 201.

Various embodiments may also include a change in optical power associated with a change in shape of a liquid meniscus 211 formed between the saline solution 207 and the oil  
20 208. In some embodiments, a change in optical power may be relatively small, such as, for example, a change of between 0 to 2.0 diopters of change. In other embodiments, a change in optical power associated with a change in shape of a liquid meniscus may be up to about 30 or more diopters of change. Generally, a higher change in optical power associated with a change in shape of a liquid meniscus 211 is associated with a relatively increased lens  
25 thickness 213.

According to some embodiments of the present invention, such as those embodiments that may be included in an ophthalmic lens, such as a contact lens, a cross cut lens thickness 213 of an arcuate liquid meniscus lens 200 will be up to about 1,000 microns thick. An exemplary lens thickness 213 of a relatively thinner lens 200 may be up to about  
30 200 microns thick. Preferred embodiments may include a liquid meniscus lens 200 with a

lens thickness 213 of about 600 microns thick. Generally a cross cut thickness of front curve lens 201 may be between about 35 microns to about 200 microns and a cross cut thickness of a back curve lens 202 may also be between about 35 microns and 200 microns. Typically, a cross-sectional profile includes a defined variance in thickness at different locations in the lens 200.

According to the present invention, an aggregate optical power is an aggregate of optical powers of the front curve lens 201 the back curve lens 202 and a liquid meniscus 211 formed between the oil 208 and the saline solution 207. In some embodiments, an optical power of the lens 200 will also include a difference in refractive index as between one or more of the front curve lens 201, the back curve lens 202, the oil 208 and the saline solution 207.

In those embodiments that include an arcuate liquid meniscus lens 200 incorporated into a contact lens, it is additionally desirable for the saline 207 and oil 208 to remain stable in their relative positions within the arcuate liquid meniscus lens 200 as a contact wearer moves. Generally, it is preferred to prevent the oil 208 from floating and moving relative to the saline 207 when the wearer moves. Accordingly, an oil 208 and saline solution 207 combination is preferably selected with a same or similar density. Additionally, an oil 208 and a saline solution 207 preferably have relatively low miscibility so that the saline solution 207 and oil 208 will not mix.

In some preferred embodiments, a volume of saline solution 207 contained within the cavity 210 is greater than the volume of oil 208 contained within the cavity 210. Additionally, some preferred embodiments include the saline solution 207 in contact with essentially an entirety of an interior surface 205 of the back curve lens 202. Some embodiments may include a volume of oil 208 that is about 66% or more by volume as compared to an amount of saline solution 207. Some additional embodiments may include an arcuate liquid meniscus lens wherein a volume of oil 208 is about 90% or less by volume as compared to an amount of saline solution 207.

Referring now to Fig. 3, a cutaway of an edge portion of an arcuate liquid meniscus lens 300 is illustrated. As discussed above, an arcuate liquid meniscus lens 300 includes combined front curve lens 301 and back curve lens 302 components. The front curve lens

301 and back curve lens 302 may be formed with one or more materials that are at least partially transparent. In some embodiments, one or both of the front curve lens 301 and the back curve lens 302 include generally optically clear plastic, such as for example, one or more of: PMMA, Zeonor and TPX.

5 One or both of the front curve lens 301 and the back curve lens 302 may be fashioned, for example via processes such as one or more of: single point diamond turning lathing; injection molding; digital mirror device free forming.

One or both of the front curve lens 301 and the back curve lens 302 may include a conductive coating 303, as illustrated, the conductive coating 303 extending along a  
10 perimeter portion from 309 to 310. In some preferred embodiments, a conductive coating 303 includes gold. The gold may be applied via a sputter process, vapor deposition or other known process. Alternative conductive coating 303 may include, by way of non-limiting example, aluminum, nickel, and indium tin oxide. Generally, the conductive coating 303 will be applied to perimeter areas of one or both of the front curve lens 301 and the back  
15 curve lens 302.

In some embodiments of the present invention, a back curve lens 302 has a conductive coating 304 applied to specific areas. For example, portions about the perimeter of the back curve lens 302 may be coated from a first boundary 304-1 to a second boundary 304-2. The gold coatings may be applied for example via a sputter process or a vapor  
20 deposition. In some embodiments, a mask may be used to apply the gold or other conductive material in a predetermined pattern around one or more perimeter portions of a front curve lens 301 or a back curve lens 302. Alternative conductive materials may be applied using various methods and covering varying areas of the back curve lens 302.

In some embodiments, a conductive pass through, such as, for example one or more  
25 holes or slots in a back curve lens 302 may be filled with a conductive filler material, such as, for example, a conductive epoxy. The conductive filler may provide electrical communication to a conductive coating on an interior surface of one or both of the front curve lens 301 and the back curve lens 302.

In another aspect of the present invention, one or both of the front curve lens 301  
30 and the back curve lens 302 may be created from multiple different materials wherein an

optical zone generally in a central area of the front curve lens 301 and the back curve lens 302 (not illustrated) may include an optically transparent material and a peripheral zone may include an optically opaque area that includes an electrically conductive material. The optically opaque area may also include one or more of control circuitry and energy sources.

5 In still another aspect, in some embodiments, an insulator coating 305 is applied to a front curve lens 301. By way of non-limiting example, the insulator coating 305 may be applied in an area from a first region 305-1 and extend to a second region 305-2. Insulators may include, for example, Parylene C™, Teflon AF or other materials with various electrical and mechanical characteristics and electrical resistance.

10 In some specific embodiments, an insulator coating 305 creates a boundary area to maintain separation between the conductive coating 303 and a saline solution 306 contained in a cavity between the front curve lens 301 and the back curve lens 302. Some embodiments accordingly include an insulator coating 305 patterned and positioned in one or more areas of one or both of the front curve lens 301 and the back curve lens 302 to  
15 prevent a positively charged conductor 303 and negatively charged saline solution 306 from coming into contact, wherein contact of a conductor 303 and a saline solution 306 will result in an electrical short circuit. Embodiments may include a positively charged saline solution 306 and a negatively charged conductor 303.

Still other embodiments may allow for a short circuit between a conductor 303 and a  
20 saline solution 306 as a reset function of circuitry associated with the operation of the lens 300. For example, a short circuit condition may equalize potential applied to the lens and cause the saline solution 306 and the oil 307 to revert to a default position.

Some preferred embodiments include a conductor 303 that extends from an area 309 on the interior of the cavity 311 to an area 310 external to the cavity 311. Other  
25 embodiments may include a channel 312 through the front curve lens or the back curve lens which may be filled with a conductive material 313, such as, for example, a waterproof conductive epoxy. The conductive material 313 may form or be connected to an electrical terminal external to the cavity. An electrical potential may be applied to the terminal and conducted to the coating via the conductive material 313 in the channel 312.

The thickness of the insulator coating 305 may be varied as a parameter of lens performance. According to the present invention, charged components, including the saline solution 306 and the conductor 303, are generally maintained on either side of the insulator coating 305. The present invention provides for an indirect relationship between the  
5 thickness of the insulator coating 305 and an electrical field between the saline solution 306 and the conductor 303, wherein the farther apart the saline solution 306 and the conductor 303 are maintained, the weaker the electrical field will be.

Generally, the present invention provides that electrical field strength may fall off dramatically as insulator coating 305 thickness increases. The closer together the fields are,  
10 the more energy that will generally be available to move a spherical liquid meniscus boundary 308. As a distance between the saline solution 306 and conductor 303 increases, the farther apart electrostatic charges of the saline solution 306 and the conductor coating 303 will be and therefore the harder it is to get the spherical liquid meniscus boundary 308 to move. Inversely, the thinner the insulator coating 305, the more susceptible is the lens to  
15 defects in an insulator coating 305. Generally, even a relatively small hole in the insulator coating 305 will create an electrical short circuit and the lens will not function in an electrowetting fashion.

In some embodiments, it is desirable to include a saline solution 306 with density that is generally the same density of an oil 307 also contained within the lens 300. For  
20 example, a saline solution 306 may preferably include a density that is within 10% of a density of an oil 307 and more preferably the saline solution 306 will include a density within 5% of a density of an oil and most preferably within about 1% or less. In some embodiments, a concentration of salts or other components within the saline solution 306 may be adjusted to adjust the density of the saline solution 306.

According to the present invention, an arcuate liquid meniscus lens 300 will provide  
25 a more stable optical quality by limiting movement of the oil 307 in relation to the front curve lens 301 and the back curve lens 302. One method of maintaining stability of movement of the oil 307 in relation to one or both of the arcuate front curve lens 301 and the back curve lens 302 is to maintain a relatively congruent density in the oil 307 and the  
30 saline solution 306. In addition, due to the curve design of the interior surfaces of both the

front curve lens 301 and the back curve lens 302, the relative depth or thickness of a layer of saline solution 306 is diminished as compared to a traditional cylindrical lens design. In this scenario, the interfacial forces acting on fluids within the cavity may have a relatively greater contribution toward maintaining an unperturbed liquid meniscus boundary 308.

5 Consequently, the density matching requirement may become more relaxed in such cases. In some embodiments, the relative thinness of the fluid layers further supports the liquid lens boundary 308.

In some preferred embodiments, the saline solution 306 provides a low refractive index as compared to the oil 307 which provides a relatively high refractive index.

10 However, in some embodiments it is possible to include a saline solution 306 with a higher refractive index as compared to the oil 307 which in such cases provides a relatively lower refractive index.

An adhesive 314 may be used to secure the front curve lens 301 and back curve lens 302 in place proximate to each other, thereby retaining the oil 307 and saline solution 306 therebetween. The adhesive 314 acts as a seal so that there is no leakage of saline solution 15 306 or oil 307 from the curved liquid meniscus lens 300.

Referring now to Fig. 4, a curved liquid meniscus lens 400 is illustrated with a liquid meniscus boundary 401 between the saline solution 406 and oil 407. According to some preferred embodiments, a meniscus wall 405 is defined in the front curve lens 404 by a first 20 angular break in an arcuate wall extending between 402 and 403. The liquid meniscus boundary 401 will move up and down the meniscus wall 405 as electrical potential is applied and removed along one or more conductive coatings or conductive materials 408.

In some preferred embodiments, a conductive coating 408 will extend from an area internal to the cavity 409 holding the saline solution 406 and the oil 407 to an area external 25 to the cavity 409 containing the saline solution 406 and oil 407. In such embodiments, the conductive coating 408 may be a conduit of an electrical potential applied to the conductive coating 408 at a point external to the cavity 409 to an area of the conductive coating 408 within the cavity 409 and in contact with the saline solution 406.

Referring now to Fig. 5, a cut away view of an edge portion of an arcuate liquid 30 meniscus lens 500 is shown with a front curve lens 501 and a back curve lens 502. The

arcuate liquid meniscus lens 500 may contain saline solution 503 and oil 504. The geometry of the arcuate liquid meniscus lens 500 and the characteristics of the saline solution 503 and oil 504 facilitate formation of a liquid meniscus boundary 505 between the saline solution 503 and oil 504.

5           Generally, a liquid meniscus lens may be viewed as a capacitor with one or more of: conductive coatings, insulator coatings, pathways, and materials present on or through the front curve lens 501 and back curve lens 502. According to the present invention, a shape of a liquid meniscus boundary 505 and therefore a contact angle between the liquid meniscus boundary 505 and the front curve lens 501 change in response to an electrical  
10 potential applied to a surface of at least a portion of one or both of the front curve lens 501 and the back curve lens 502.

          According to the present invention, a change in an electrical potential applied to the saline solution 503 via the conductive coatings or materials changes a position of the liquid meniscus boundary 505 along a meniscus wall 506. The movement takes place between a  
15 first sharp 506-1 and a second sharp 506-2.

          In preferred embodiments, the liquid meniscus boundary 505 will be at or near the first sharp 506-1 when a first magnitude of electrical potential is applied to the lens, such as, for example, a voltage and current correlating with an unpowered state or resting state.

          Application of a second magnitude of electrical potential, sometimes referred to as a  
20 first powered state, may correlate with a movement of the liquid meniscus boundary 505 along the meniscus wall 506 generally in the direction of the second sharp 506-2, causing the shape of the liquid meniscus boundary to change. As discussed further below, according to the present invention, each of multiple sharps included along a meniscus wall may be associated with respective powered states.

25           An applied voltage for transitioning between a first powered state and a second powered state may include, for example, a direct current voltage of between about 5 volts to about 60 volts. In other embodiments an alternating current voltage may also be utilized.

          In some embodiments, the meniscus wall 506 will be a smooth surface in relation to the thickness of the insulator coating. A smooth meniscus wall 506 surface may minimize

defects in the insulator coating. Additionally, because random irregularities in surface texture may result in uneven fluid motion and therefore cause uneven or unpredictable meniscus motion when energizing or de-energizing the lens, a smooth meniscus wall 506 is preferred. In some preferred embodiments, a smooth meniscus wall includes a peak to valley measurement along the meniscus wall 506 in the range of between about 1.25 nanometers to 5.00 nanometers.

In another aspect, in some embodiments, it is desirable for the meniscus wall 506 to be hydrophobic, in which case a defined texture, such as a nano-textured surface, may be incorporated in the design of the arcuate liquid meniscus lens.

In still another aspect, in some embodiments, the meniscus wall 506 may be angled relative to an optical axis of the lens. The angle can range from  $0^\circ$ , or parallel to the optical axis, to at or near  $90^\circ$ , or perpendicular to the optical axis. As illustrated, and in some preferred embodiments, the meniscus wall 506 angle is generally between about  $30^\circ$  and  $50^\circ$  in order for the arcuate liquid meniscus lens to function given the current contact angle between the liquid meniscus boundary 505 and the insulator-coated meniscus wall 506. With the use of different materials or with different optical objectives, such as telescopic vision, the angle of the meniscus wall 506 may be closer to  $0^\circ$  or  $90^\circ$ .

According to the present invention, an angle of a meniscus wall 506 may be designed to accommodate a magnitude of movement along a meniscus wall 506 upon application of a specified electrical voltage. In some embodiments, as meniscus wall 506 angle increases, the ability to change lens power generally decreases within given lens size and voltage parameters. Additionally, if the meniscus wall 506 is at or near  $0^\circ$  relative to the optical axis, the liquid meniscus boundary 505 will be steered nearly straight onto the front optic. Meniscus wall angle is one of several parameters that can be tailored to provide various outcomes in lens performance.

In some preferred embodiments, the meniscus wall 506 is approximately 0.265 mm in length. However, the angle of the meniscus wall 506 together with the size of the overall lens will naturally affect meniscus wall 506 length in various designs.

It may generally be considered that an arcuate liquid meniscus lens 500 will fail if the oil 504 contacts the back curve lens 502. Therefore, in preferred embodiments, the meniscus wall 506 is designed to allow a minimum clearance of 50 microns between the

first sharp 506-1 and the back curve lens 502 at its nearest point. In other embodiments, the minimum clearance may be less than 50 microns, although the risk of lens failure increases as the clearance is reduced. In yet other embodiments, the clearance may be increased to mitigate the risk of lens failure, but the overall lens thickness will also increase which may be undesirable.

In still another aspect of some preferred embodiments of the present invention, the behavior of a liquid meniscus boundary 505 as it travels along a meniscus wall 506 may be extrapolated using Young's Equation. Although Young's Equation defines the balance of forces caused by a wet drop on a dry surface and assumes a perfectly flat surface, the fundamental properties can be applied to the electrowetted lens environment created within the arcuate liquid meniscus lens 500.

A first magnitude of electrical energy may be applied to the lens, such as, for example, when the lens is in an unpowered state. During the application of the first magnitude of electrical energy, a balance of interfacial energies between the oil 504 and saline solution 503 is achieved. Such a state may be referred to herein as a liquid meniscus boundary 505. The oil 504 and meniscus wall 506, and the saline solution 503 and meniscus wall 506, form an equilibrium contact angle between the liquid meniscus boundary 505 and the meniscus wall 506. When a change in magnitude of voltage is applied to the arcuate liquid meniscus lens 500, the balance of interfacial energies will change, resulting in a corresponding change in contact angle between the liquid meniscus boundary 505 and the meniscus wall 506.

The contact angle of the liquid meniscus boundary 505 with the insulator-coated meniscus wall 506 is an important element in the design and function of the arcuate liquid meniscus lens 500 not only due to its role in the Young's Equation in movement of the liquid meniscus boundary 505, but also because the contact angle is used in conjunction with other features of the arcuate liquid meniscus lens 500 to limit meniscus movement.

Discontinuities, such as sharps 506-1 and 506-2, at both ends of the meniscus wall 506 act as boundaries for liquid meniscus 505 movement because it would require a significant change in applied electrical potential to effect a large enough change in liquid meniscus contact angle to move the liquid meniscus boundary 505 past one of the sharps. By way of non-limiting example, in some embodiments, a contact angle of the liquid

meniscus boundary 505 with the meniscus wall 506 is in the range of  $15^{\circ}$  to  $40^{\circ}$  whereas the contact angle of the liquid meniscus boundary 505 with the step 507 beyond the second sharp 506-2 is perhaps in the range of  $90^{\circ}$  to  $130^{\circ}$  and in some preferred embodiments about  $110^{\circ}$ .

5           A voltage may be applied to the lens, resulting in movement of the liquid meniscus boundary 505 along the meniscus wall 506 toward the second sharp 506-2. The natural contact angle of the liquid meniscus boundary 505 with the insulator-coated meniscus wall 506 will cause the liquid meniscus boundary 505 to stop at the second sharp 506-2 unless significantly more voltage is supplied.

10           At one end of the meniscus wall 506, a first sharp 506-1 generally defines one limit beyond which the liquid meniscus boundary 505 will not typically move. In some embodiments, the first sharp 506-1 is constructed as a sharp edge. In other preferred embodiments, the first sharp 506-1 has a defined small radial surface which can be created with less possibility of defect. Conductive, insulator, and other possible desired coatings  
15           may not deposit evenly and predictably on a sharp edge, whereas a defined radius edge of the radial surface can be coated more reliably.

          In some embodiments, the first sharp 506-1 is constructed at about a  $90^{\circ}$  angle with a defined radius of about 10 microns. The sharp may also be created with less than a  $90^{\circ}$  angle. In some embodiments, a sharp with a larger angle than  $90^{\circ}$  may be used to increase  
20           the sturdiness of the sharp, but the design would then take up more lens space.

          In various embodiments, a defined radius of a sharp 506-1 and/or 506-2 may be in the range of 5 microns to 50 microns. A larger defined radius may be used to improve the reliability of the coatings, but at the cost of using more space within the tight confines of the lens design. In this, as in many other areas of lens design, tradeoffs exist between ease of  
25           construction, optimization of lens functions, and minimizing size. A functional, reliable arcuate liquid meniscus lens 500 may be made using a wide range of variables.

          In some embodiments, a larger sharp radius may be used in conjunction with an improved surface finish on a side-wall between two adjacent sharps. In some embodiments, it may be desirable that a surface from a first radius (sharp) to a second radius (sharp) be  
30           smooth and without discontinuities wherein it is helpful to cut a mold used to fashion a sharp with the same tool. Radii included in a sharp may be cut into a mold tool surface,

wherein the mold tool surface radius is larger than the sharp radius. Wherein the mold tool surface is a continuous surface including one or more sharps and a side wall. A larger tool radius may generally relate to a smoother surface finish of a corresponding cut.

A second sharp 506-2, includes a feature designed to limit oil movement when voltage is applied to the arcuate liquid meniscus lens 500. The second sharp 506-2 may also include, in some embodiments a generally pointed end, or in other embodiments, the second sharp 506-2 may include a defined radius of between 5 and 25 microns, most preferred 10 microns. A 10 micron radius performs well as a sharp and can be created using single point diamond turning lathe or injection molding processes.

A vertical or nearly vertical step 507, extending to a start of the optical area 508 of the front curve lens 501 may be included on a side of the second sharp 506-2 opposing the meniscus wall 506. In some embodiments, the step 507 is 120 microns in height, although it could be in the range of 50 to 200 microns.

In some embodiments, the step 507 may be angled at about 5° from optical axis. In other embodiments, the step 507 angle may be as little as 1° or 2° or may be angled more than 5°. A step 507 that is less angled from optical axis will generally act as a more effective limiter of meniscus movement because it would require a greater change in the contact angle of the liquid meniscus boundary 505 to move off of the meniscus wall 506 and onto the step 507. The transition from the step 507 to the start of the optical area 508 is a 25 micron radius. A larger radius would unnecessarily consume more space within the lens design. A smaller radius is possible and may be implemented if necessary to gain space. The decision to use a defined radius rather than a theoretical sharp in this area as well as others in the lens is based, in part, on the potential move to an injection molding process for lens elements. A curve between the step 507 and the start of the optical area 508 will improve plastic flow during the injection molding process and result in a lens with optimal strength and stress-handling characteristics.

Referring now to Fig. 6A, in some embodiments a multi-step meniscus wall 601 is depicted which may be found in a liquid meniscus lens. The multi-step meniscus wall 601 includes multiple linear segments 608 each of which is at the same angle relative to an optical axis. At one end of each linear segment 608 is found a step 609 comprised of a relatively smaller linear segment when compared to a linear segment 608, and placed nearly

parallel to an optical axis. The multiple linear segments and steps may or may not be interspersed with segments of a meniscus wall that include other shapes in relation to the optical axis, such as, for example, a convex shape or a concave shape. Other shaped features and segments may also be interspersed.

5           In some embodiments, a multi-step meniscus wall 601 may be placed at approximately a forty five degree ( $45^\circ$ ) angle from an optical axis in an arcuate liquid meniscus lens containing oil 602 and saline solution 603. In some embodiments, a liquid meniscus boundary 604A contacts the multi-step meniscus wall 601 at 605A in a first state of potential applied to the multi-step wall 601, such as, for example, in an unpowered state.  
10       Generally, in some exemplary embodiments, the first powered state includes the liquid meniscus boundary near the end of the multi-step meniscus wall 601 closest to a first sharp 607.

          Fig. 6B depicts the location of a liquid meniscus boundary 604B in a second powered state, such as a powered state with a voltage applied to the meniscus wall 601. In  
15       relation to a first state, including an unpowered state, the liquid meniscus boundary 604B has moved generally toward the front curve lens 606 along the multi-step meniscus wall 601. The powered state may also include a liquid meniscus boundary 604B generally nearer to a step 609 between linear segments in the multi-convex meniscus wall 601.

          Referring now to Fig. 7A, in some embodiments a multi-gradient meniscus wall 701  
20       is depicted which may be found in a liquid meniscus lens. The multi-gradient meniscus wall 701 includes multiple linear segments 708 at slightly varying angles from optical axis. The multiple linear segments may or may not be interspersed with segments of a meniscus wall that include other shapes in relation to the optical axis, such as, for example, a convex shape or a concave shape. Other shaped features and segments may also be interspersed.

25           In some embodiments, a multi-gradient meniscus wall 701 may be placed at approximately a forty five degree ( $45^\circ$ ) angle from an optical axis in an arcuate liquid meniscus lens containing oil 702 and saline solution 703. In some embodiments, a liquid meniscus boundary 704A contacts the multi-gradient meniscus wall 701 at 705A in a first state of power applied to the multi-gradient wall 701, such as, for example, in an unpowered  
30       state. Generally, in some exemplary embodiments, the first powered state includes the

liquid meniscus boundary near the end of the multi-gradient meniscus wall 701 closest to a first sharp 707.

Fig. 7B depicts the location of a liquid meniscus boundary 704B in a second powered state, such as a powered state with an electrical potential applied to the meniscus wall 701. In relation to a first state, including an unpowered state, the liquid meniscus boundary 704B has moved generally toward the front curve lens 706 along the multi-gradient meniscus wall 701. The powered state may also include a liquid meniscus boundary 704B generally nearer to a discontinuity 709 between linear segments in the multi-convex meniscus wall 701.

Referring now to Fig. 8A, a perspective view of a multi-step meniscus wall 801A component of an arcuate liquid meniscus lens is shown separately from other portions of an arcuate liquid meniscus lens. In the illustrated embodiments, a multi-step meniscus wall 801A includes three linear meniscus wall segments, 801A-1 through 801A-3. The wall segments are angled in relation to an optical axis 804 through the lens. Other embodiments may include more or less linear meniscus wall segments 801A-1 through 801A-3. A number of wall segments may be based upon, for example, a physical size of a liquid meniscus lens, a number of set positions of meniscus the lens is anticipated to deploy, or other concerns. The multi-step meniscus wall 801A is of a consistent length between the first sharp 802A and the edge of the optical zone 803A around the entire lens.

In Fig. 8B is found a perspective view of the multi-gradient meniscus wall 801B component of an arcuate liquid meniscus lens shown separately from other portions of an arcuate liquid meniscus lens. In the illustrated embodiment, the multi-gradient meniscus wall 801B includes four linear segments, 801B-1 through 801B-4. The wall segments are angled in relation to an optical axis 804 through the lens. Other embodiments may include more or less linear meniscus wall segments 801B-1 through 801B-4. A number of wall segments may be based upon, for example, a physical size of a liquid meniscus lens, a number of set positions of a meniscus the lens is anticipated to deploy, or other concerns. The multi-gradient meniscus wall 801B is of a consistent length between the first sharp 802B and the edge of the optical zone 803B around the entire lens.

Depicted in Fig. 8C is a perspective view of one linear meniscus wall segment 801-1, the shape of which comprises a frustum of a cone. It may represent a segment of a multi-

step meniscus wall such as 801A-1 from Fig. 8A, or a segment of a multi-gradient meniscus wall such as 801B-1 from Fig. 8B.

Fig. 6C combines Figs. 6A and 6B, showing the location of the liquid meniscus boundary in both an unpowered 604A state and a powered 604B state. According to the present invention, a liquid meniscus lens with a multi-step meniscus wall 601 placed at a given angle relative to an optical axis, as shown in Fig. 6C, provides more consistent and repeatable control over liquid meniscus movement resulting from the application of an electrical potential to a meniscus wall portion than a liquid meniscus lens with a linear meniscus wall placed at a similar angle relative to the optical axis. Examples of a lens including a linear meniscus wall are described in the U.S. Patent Application Serial Number 61,359,548, filed June 29, 2010 and entitled, "LENS WITH CONICAL FRUSTUM MENISCUS WALL".

In some preferred embodiments, a voltage is applied to a meniscus wall and a corresponding liquid meniscus boundary moves along the multi-step meniscus wall 601 toward the front curve lens 606. Steps 609 at the end of each linear segment 608 are functional to slow and stop liquid meniscus movement at designated zones to achieve specific add power changes or other desirable liquid meniscus boundary movement. As the liquid meniscus boundary travels along each linear segment 608, it is slowed and more easily stopped near each step 609 due to changes in liquid meniscus boundary contact angle at the junction between the linear segment 608 and the step 609.

Similarly, Fig. 7C combines Figs. 7A and 7B, showing the location of the liquid meniscus boundary in both an unpowered 704A state and a powered 704B state. According to the present invention, a liquid meniscus lens with a multi-gradient meniscus wall 701 placed at a given angle relative to an optical axis, as shown in Fig. 7C, provides more consistent and repeatable control over liquid meniscus movement resulting from the application of an electrical potential to a meniscus wall portion than a liquid meniscus lens with a linear meniscus wall placed at a similar angle relative to the optical axis. Examples of a lens including a linear meniscus wall are described in the U.S. Patent Application Serial Number 61,359,548, filed June 29, 2010 and entitled "LENS WITH CONICAL FRUSTUM MENISCUS WALL".

In some preferred embodiments, a voltage is applied to a meniscus wall and a corresponding liquid meniscus boundary moves along the multi-gradient meniscus wall 701 toward the front curve lens 706. Discontinuities 709 between linear segments 708 are functional to slow and stop liquid meniscus movement at designated zones to achieve specific add power changes or other desirable liquid meniscus boundary movement. As the liquid meniscus boundary travels along each linear segment 708, it is slowed and more easily stopped near each discontinuity 709 due to changes in liquid meniscus boundary contact angle at the discontinuity 709 between linear segments 708.

In some embodiments, a net effect of the present invention includes a predictable, small contact angle hysteresis which helps to stabilize the position of the liquid meniscus boundary in spite of small voltage fluctuations. Furthermore, oil droplets may be retained by the channel structures when the position of the liquid meniscus boundary is caused to change by applied voltage. The oil droplets assist with retraction of the liquid meniscus boundary when the lens is de-energized, leading to a faster and more predictable recovery time.

While the invention has been described with reference to particular embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from the scope of the invention.

Therefore, it is intended that the invention not be limited to the particular embodiments disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope and spirit of the appended claims.

## CLAIMS

1. An optical lens comprising:
  - a front lens comprising a front lens exterior surface and a front lens interior  
5 surface;
  - a back lens comprising a back lens interior surface and a back lens exterior surface, said back lens positioned proximate to said front lens such that said front lens interior surface and said back lens interior surface form a cavity therebetween;
  - a volume of saline solution and oil contained within the cavity formed between  
10 said front lens interior surface and said back lens interior surface, said volume of saline solution and oil comprising a meniscus therebetween; and
  - a meniscus wall formed on an area of the interior surface of the front lens, the meniscus wall comprising multiple portions each in the shape of a discrete frustum of a cone formed in the front lens and bordering the meniscus formed between the saline  
15 solution and oil.
2. The optical lens of claim 1 wherein at least one of the front lens and the back lens is essentially flat.
- 20 3. The optical lens of claim 1 wherein the front lens and the back lens comprise an arcuate lens.
4. The optical lens of claim 3 additionally comprising a conductive coating on at least a portion of said meniscus wall.  
25
5. The optical lens of claim 4 wherein the volume of oil is less than the volume of saline solution contained within the cavity.
6. The optical lens of claim 5 wherein the volume of oil comprises about 66% or  
30 more by volume as compared to an amount of saline solution.
7. The optical lens of claim 5 wherein the volume of oil comprises about 90% or less by volume as compared to an amount of saline solution.

8. The optical lens of claim 4 wherein the volume of oil comprises a density about equal to a density of the saline solution.
9. The optical lens of claim 4 wherein the volume of oil comprises density within  
5 about 10% of a density of the saline solution.
10. The optical lens of claim 4 wherein the volume of oil comprises density within about 5% of a density of the saline solution.
- 10 11. The optical lens of claim 4 wherein the conductive coating extends from an area interior to the cavity to an area external to the cavity.
12. The optical lens of claim 11, wherein the area of conductive coating external to the cavity forms an electrical terminal for providing an electrical charge to the liquid  
15 meniscus lens.
13. The optical lens of claim 11 wherein the saline solution and the oil form a meniscus and an application of an electrical potential to the area of conductive coating external to the cavity causes a change in position of contact of the meniscus along the  
20 meniscus wall.
14. The optical lens of claim 13 wherein the electrical potential comprises a direct current.
- 25 15. The optical lens of claim 13 wherein the electrical potential comprises between about 5.0 volts to 60.0 volts.
16. The optical lens of claim 15 wherein the electrical potential comprises about 20.0 volts.  
30
17. The optical lens of claim 15 wherein the electrical potential comprises about 5.0 volts.
18. The optical lens of claim 13 wherein the electrical potential comprises between  
35 about 3.5 volts to about 7.5 volts.

19. The optical lens of claim 5 wherein the front curve lens exterior surface comprises an optical power other than about 0.
20. The optical lens of claim 5 wherein the front curve lens interior surface  
5 comprises an optical power other than about 0.
21. The optical lens of claim 5 wherein the back curve lens exterior surface comprises an optical power other than about 0.
- 10 22. The optical lens of claim 5 wherein the back curve lens interior surface comprises an optical power other than about 0.
23. The optical lens of claim 5 additionally comprising a channel through one or both of the front curve lens and the back curve lens and a conductive material filling the  
15 channel.
24. The optical lens of claim 23 additionally comprising a terminal in electrical communication with the conductive material filling the channel.
- 20 25. The optical lens of claim 24 wherein application of an electrical potential to the terminal causes a change in the shape of the meniscus.
26. The optical lens of claim 5 additionally comprising an insulator coating along at least a portion of the interior surface of the front curve lens, wherein the insulator  
25 coating comprises an electrical insulator.
27. The optical lens of claim 26, wherein the insulator comprises one of Parylene C™ and Teflon AF.
- 30 28. The optical lens of claim 26 wherein the insulator comprises a boundary area to maintain separation between the conductive coating and a saline solution contained in the cavity between the front curve lens and the back curve lens.
29. The optical lens of claim 5 wherein an angle of the multiple conical frustums  
35 comprising the meniscus wall comprises between about 30° and 50°.

30. The optical lens of claim 29 additionally comprising a meniscus sharp adjacent to the meniscus wall, said sharp comprising an angular feature for containing the volume of saline solution and oil.
- 5 31. The optical lens of claim 29 wherein the sharp comprises a radial surface portion.
32. The optical lens of claim 31 wherein the radial surface portion comprises a radius in the range of 5 microns to 25 microns.