

**METHODS AND SYSTEMS FOR PRODUCING COATED OPTICAL SUBSTRATES,  
AND PHOTOCHROMIC INK FORMULATIONS THEREFOR**

**CROSS-REFERENCE TO OTHER PUBLICATIONS**

This application claims priority from US patent application nos. 63/580,003, filed on September 1, 2023; 63/541,293, filed on September 28, 2023; 63/541,279, filed on September 28, 2023; 63/541,292, filed on September 28, 2023; as well as from GB application nos. 2409920.2, filed on July 8, 2024, and GB2409979.8, filed on July 9, 2024; the teachings of all of which are incorporated herein by reference.

**FIELD AND BACKGROUND OF THE INVENTION**

The present invention relates to coated optical and ophthalmic devices and articles having photochromic coatings, to formulations for producing such coated devices and articles, and to systems and methods for applying such formulations to form such photochromic coatings on these devices and articles.

Commercial, high-throughput production of eyeglass coatings is often performed using various analog coating process such as dipping and spin coating processes.

Ultra-thin anti-reflective coatings having a thickness of 200 to 300 nanometers may be applied, layer-by-layer, by means of vacuum deposition.

In various known processes, optical impediments may be appreciably exacerbated when the target surface is a curved optical surface such as an eyeglass lens, and particularly, for eyeglass lenses having high SAG numbers or base curves.

The present inventors have recognized a need for improved optical and ophthalmic devices and articles having photochromic coatings, for improved photochromic formulations, and for systems and methods of producing such devices and articles.

**SUMMARY OF THE INVENTION**

According to some teachings of the present invention there is provided an ink formulation comprising: (a) a resin; (b) a photochromic dye; (c) a softening agent for softening the resin; and (d) a solvent system including a very low vapor-pressure solvent **LLevap** and at least one of a high vapor-pressure solvent (**Hevap**) and a very high vapor-pressure solvent (**HHevap**); wherein the softening agent is optionally a non-volatile liquid softening agent; and wherein the resin and the photochromic dye are dissolved within the solvent system.

According to further teachings of the present invention there are provided methods and systems for producing an optical construction on a curved, polymeric optical substrate, one such method including: (a) microvalving drops of a liquid, photochromic dye containing formulation

onto an optical surface of the optical substrate, to form a wet layer; and (b) treating the wet layer to produce a dried photochromic dye containing layer on the optical surface.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The invention is herein described, by way of example only, with reference to the accompanying drawings. With specific reference now to the drawings in detail, it is stressed that the particulars shown are by way of example and for purposes of illustrative discussion of the preferred embodiments of the present invention only, and are presented in the cause of providing what is believed to be the most useful and readily understood description of the principles and conceptual aspects of the invention. In this regard, no attempt is made to show structural details of the invention in more detail than is necessary for a fundamental understanding of the invention, the description taken with the drawings making apparent to those skilled in the art how the several forms of the invention may be embodied in practice. Throughout the drawings, like-referenced characters are used to designate like elements.

In the drawings:

Fig. 1 provides a schematic block diagram of a method of treating an optical surface, according to aspects of the present invention;

Fig. 2 provides a schematic block diagram of a method of treating an optical surface to produce a photochromic layer, according to aspects of the present invention;

Fig. 3 provides optional steps for the schematic block diagram of Figure 2, in which the pre-treatment may include the applying of a liquid primer formulation to the exposed surface of the ophthalmic substrate, along with subsequent drying/curing;

Fig. 4 is a schematic cross-sectional view of a multi-layered ophthalmic structure, which includes an ophthalmic substrate having a photochromic, ophthalmic construction fixedly attached to a broad surface of the substrate;

Figures 4A and 4B are schematic representations of a microvalve apparatus jetting ink drops onto a convex lens surface and onto a concave lens surface, respectively;

Fig. 5 shows a conceptual representation of a process for coating and finishing an optical or ophthalmic substrate using a coating system, according to embodiments of the present invention;

Fig. 6A, 6B and 6C show respective block diagrams of exemplary coating systems according to embodiments of the present invention;

Fig. 7A and 7B show respective conceptual representations of a process for coating an optical or ophthalmic substrate using a coating system in conjunction with a surface treatment apparatus, according to embodiments of the present invention;

Fig. 8 shows a block diagram of an exemplary coating system according to embodiments of the present invention;

Fig. 9 shows a block diagram of an exemplary surface treatment apparatus according to embodiments of the present invention;

Figs. 10A, 10B, 10C and 11 show respective conceptual representations of processes for coating and drying an optical or ophthalmic substrate, according to embodiments of the present invention;

Figs. 12A, 12B, 12C and 12D show respective schematic views of exemplary optical substrates according to embodiments of the present invention;

Figs. 13A and 13B show respective side and perspective schematic views of a virtual two-dimensional projection of a curved surface of an optical substrate according to embodiments of the present invention;

Fig. 14 shows a schematic side view of drop deposition on a curved surface of an optical substrate in accordance with a virtual two-dimension projection of the surface, according to embodiments of the present invention;

Fig. 15 shows a schematic top view of an optical substrate including a virtual annulus comprising an edge portion according to embodiments of the present invention; and

Fig. 16 shows a schematic side view of an optical substrate having a curved surface, showing certain aspects of the surface geometry according to embodiments of the present invention.

#### DESCRIPTION OF THE PREFERRED EMBODIMENTS

The principles and operation of the optical constructions according to the present invention may be better understood with reference to the drawings and the accompanying description.

Before explaining at least one embodiment of the invention in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of the components set forth in the following description or illustrated in the drawings. The invention is capable of other embodiments or of being practiced or carried out in various ways. Also, it is to be understood that the phraseology and terminology employed herein is for the purpose of description and should not be regarded as limiting.

The inventors have found that applying one or more optical coatings to an optical substrate involves a variety of technological hurdles. Some of these relate to optical substrates, which tend to be highly smooth, and substantially non-absorbent. Optical substrates are generally transparent, and may require a high degree of transparency from the plurality of optical

coatings. Moreover, the refractive index of each coating, or of all the coatings together, may be constrained to be similar to that of the optical substrate.

The optical construction or article produced must satisfy mechanical criteria such as hardness and/or scratch resistance. Each of the coatings must also be relatively inert to the other coatings in contact therewith. Moreover, since the coatings may be applied successively, at least one of the applied wet, or uncured, formulations may contact, and interact with, a previously applied coating.

The curing time of each coating or layer should be reasonable (at most minutes or hours), and the curing temperature should be sufficiently low so as not to damage the optical substrate, nor to damage any previously applied coatings.

The adhesion to the optical or ophthalmic substrate and resistance to peeling or cracking of the coating or coatings may also be crucial to obtaining a viable coated lens such as a coated ophthalmic lens.

From a throughput standpoint, it would be advantageous to apply very large ink drops (e.g., on the order of nanoliters, and not picoliters) on such curved, smooth eyeglass surfaces.

The inventors have found, however, that such large ink drops -- even with precise digital application -- disadvantageously detract from image resolution.

Moreover, ink drops tend to slip on such curved, smooth eyeglass surfaces, particularly in the case of low-viscosity ink drops. Such uncontrolled flow may make the ultimate positioning of the drops decidedly non-deterministic. This problem is exacerbated for large, nanoliter-size (e.g., having a volume of 10 nanoliters) drops: relative to picoliter-size drops, which have about 1/1000 the volume, as the volume to surface area of the nanoliter-size ink drop is manifestly high, as is the volume of the drop to the contact area of the deposited drop. Consequently, the inventors have found that various surface-based fixation means (e.g., an adhesive underlayer) may be of limited efficacy, such that the deposition of such nanoliter-size drops may disadvantageously produce a non-continuous or at least non-even wet layer, resulting in bald spots, haze, uneven thickness, uneven optical density, and other optical impediments in the finished product.

While spinning, rotating, etc., have been contemplated in attempts to produce smooth and even wet layers, the inventors have found that such methods fail to meet various technological challenges, and may add significant technological disadvantages of their own, particularly within the framework of industrial settings.

It would thus be highly desirable to produce ophthalmic-quality, thin, continuous, smooth wet layers, without employing these methods. For colored layers and coatings, it would be further desirable for the optical density to be even, at least as discernable by the naked eye.

It will be appreciated that for highly curved lens surfaces (e.g., base curve 4, base curve 6 or higher), the problem of uncontrolled flow becomes even more severe, particularly for large lens diameters.

Moreover, the inventors have further found that in the production of ultra-thin (e.g., having a dry thickness of at most 2 $\mu$ m, at most 1.6  $\mu$ m, or at most 1.2  $\mu$ m) optical coatings, the potential for optical impediments in the finished product may be yet further pronounced.

Without wishing to be limited by theory, the inventors believe that the microvalving of a continuous, relatively smooth and even layer of photochromic dye-containing ink on an optical surface (and more particularly, on a curved optical surface such as an eyeglass lens) may be effected by achieving the conditions of “controlled flow” of the ink on the optical surface. When the photochromic ink drops are microvalved on the optical surface without fixation means (e.g., when the solvent is predominantly a low evaporation rate solvent), the applied photochromic dye-containing ink may disadvantageously flow in a substantially uncontrolled fashion, which may result in at least one of flooding, bald spots, coffee ring type effects, uneven layer thickness, and uneven color intensity within the layer. Moreover, by covering the entire surface of the substrate with ink drops, the flooding phenomenon may appreciably worsen. However, when the ink drops are quickly and heavily fixated on the optical surface (e.g., when the solvent is predominantly a very-high evaporation rate solvent), the dye-containing layer may not be continuous, or even if continuous, may lack the requisite smoothness and evenness required for optical and ophthalmic layers and coatings.

The inventors have found that by balancing the solvent system with a particular mixture of relatively low and high evaporation rate solvents, a degree of controlled flow may be achieved, which surprisingly may result in a layer having the requisite smoothness and evenness required for photochromic optical and ophthalmic layers or coatings.

Methods and systems for achieving such controlled flow are provided hereinbelow.

As schematically presented in Figure 1, the inventive method includes microvalving (i.e., jetting via a microvalve) drops of a liquid, photochromic dye containing formulation onto an optical surface of an optical substrate, to form a wet layer (step 102).

The microvalving of the photochromatic formulation onto the optical/ophthalmic substrate may be performed utilizing various microvalving technologies, all of which utilize a microvalve.

The microvalve may be a component within a microvalve system, and several microvalves can be utilized, preferably in parallel, to improve throughput.

Typically, the microvalving of the photochromatic formulation is performed according to a pre-determined pattern such as a pre-determined digital pattern.

In some embodiments, the microvalve is piezo-actuated (e.g., using a Nordson Pulse Jet Valve, a Vermetics MDS 1560 Series, or a Techcon 9800 series);

In some embodiments, the microvalve is electromagnetically actuated (e.g., using a solenoid valve). The fluid or dispersion flows through the microvalve directly. When a current is applied through the valve coil, a mobile anchor attached to a valve ball is magnetically pulled by the magnetic field of a stationary anchor. The microvalve opens, discharging a portion of the medium. When no current is applied, the microvalve is closed, as a closing spring acts on the mobile anchor associated with the valve ball.

Exemplary microvalves of this type are manufactured by Fritz Gyger AG and by the Lee company.

In some embodiments, the microvalve is electro-pneumatically actuated. Exemplary microvalves of this type are the Liquidyn® P-Jet Series, manufactured by Nordson.

In some embodiments, the optical surface is a curved optical surface such as a curved lens surface.

In some embodiments, the optical surface is a polymeric surface.

In some embodiments, the optical substrate is an ophthalmic substrate, and the optical surface is an ophthalmic surface.

In some embodiments, the ophthalmic substrate is a prescription lens such as an eyeglass lens.

The term “ophthalmic substrate”, as used herein, refers to a substrate that is used by the human eye to view therethrough. The ophthalmic substrate is a component of an ophthalmic device or system, or an ophthalmic component of such a device or system. Typically, the ophthalmic substrate is a lens, and the ophthalmic surface is a surface of the lens.

More generally, the term “ophthalmic”, as used herein to modify a structure, such as a “substrate”, “surface”, “construction”, “structure”, “device”, “arrangement”, and “system”, refers to the property of that structure that enables the human eye to effectively view an object therethrough. While a coated lens is a typical example of an ophthalmic device, other applications will be appreciated by those of skill in the art, including, by way of example, a helmet having a transparent visor.

An ophthalmic construction may consist of, or include, an ophthalmic component of such an ophthalmic device or system.

With regard to the photochromic ink wet layer, at least one of a thickness  $TH$ , characteristic thickness  $TH_c$ , and average thickness  $TH_{av}$  of the wet layer (and typically any two or all three of  $TH$ ,  $TH_c$ , and  $TH_{av}$ ) is at most 100 micrometers ( $\mu m$ ), or at most 80  $\mu m$ , and more typically, at most 70  $\mu m$ , at most 60  $\mu m$ , or at most 50  $\mu m$ .

Typically, at least one of TH, THc, and THav (and typically any two or all three of TH, THc, and THav) is at least 10 $\mu$ m, at least 14 $\mu$ m, at least 18 $\mu$ m, at least 25 $\mu$ m, at least 30 $\mu$ m, at least 40 $\mu$ m, or at least 45 $\mu$ m.

The method may further comprise treating the wet layer to produce a dried photochromic dye containing layer on the optical surface (step 104). The treating includes drying and/or curing the wet layer. The nature of the formulation may largely determine the preferred method of curing.

Thus, in some embodiments, the drying/curing (formation of a film) is essentially or solely effective by drying (solvent evaporation), e.g., when the polymer is dissolved (e.g., vinyl ester resins or alkyd resins in organic solvent) or dispersed (e.g., aqueous dispersions such as PUDs), or in the form of an emulsion (e.g., styrene-acrylic emulsion polymers). Such drying is typically conducted at elevated temperatures ("thermal drying").

In some embodiments, the drying/curing is effected by chemical drying/curing (e.g., polymerization from pre-polymers -- monomers and oligomers; cross-linking of polymers, oxidative chemical curing, e.g., using ambient oxygen; cationic or radical curing, e.g., using UV radiation; oxidative chemical curing, e.g., using ambient oxygen; moisture-scavenging chemical curing, e.g., using ambient humidity).

In some embodiments, the chemical drying/curing is or includes curing by actinic radiation, i.e., by electromagnetic radiation (e.g., UV radiation, electron beam, IR, and microwave) that is capable of initiating a chemical reaction.

The drying/curing of the wet layer may advantageously be performed so as to achieve a "fully cured" layer or coating. The inventors have found that partially cured layers may result in solvent attack, migration, mixing, etc. from an adjacent or subsequently-applied layer in the stack. These phenomena may appreciably detract from optical quality.

In addition, and with particular reference to solvent attack, the penetration of solvent from a subsequently applied layer may compromise the adhesion at the interface between these layers, and at the interface between the two previously applied layers, or between the previously applied layer and the substrate. Thus, fully curing of the wet layer may be cardinal in producing an optical stack or construction having both suitable optical and mechanical properties.

Significantly, the inventors have found that solvent systems containing both high and low evaporation rate solvents may appreciably mitigate the extent of solvent penetration, when such penetration cannot be completely avoided.

Further methods of producing high-quality optical stacks will be evident from the description below.

As used herein in the specification and in the claims section that follows, the term “SAGITTA”, or “SAG”, with reference refers to the convex or concave curvature of an optical substrate, represents the physical distance between the vertex (the highest point of the convex curvature) along the curved surface of the optical substrate and the center point of a line drawn perpendicular to the curved surface from one edge of the optical substrate to the other. The SAG may be measured, or determined according to the following established equation:

$$\text{SAG} = |R| - \sqrt{R^2 - \left(\frac{D}{2}\right)^2}$$

wherein R is the radius of curvature of the optical surface and D is the diameter thereof.

In some embodiments, the SAG number of the optical substrate is at least 0.5mm, at least 1mm, at least 2mm, at least 3.5mm, at least 5mm, or at least 6mm.

Typically, the SAG number of the optical substrate is at most 15mm, at most 13.5mm, at most 12mm, or at most 10.5mm.

The base curve of the optical substrate may be at least 2, at least 3, at least 4, at least 5, at least 6, or at least 8.

The base curve may be at most 14, and more typically, at most 12 or at most 10. At higher base curves and SAG numbers, the flow of ink on the optical surface may be sufficiently uncontrolled as to compromise the optical quality of the layer or coating.

As used herein, the term “base curve” refers to the theoretical base curve, or “true curve”.

Similarly, the phenomenon of uncontrolled flow may also be correlated with the angle  $\alpha$  (discussed in further detail hereinbelow) of the lens. The methods of the present invention are generally suitable for controlling flow on the lens for an  $\alpha$  of up to 37°, up to 42°, or even up to 50°.

In some embodiments, the photochromic ink formulation may comprise a resin, a photochromic dye, and a solvent system including a very low vapor-pressure solvent (**LLevap**) and at least one of a low vapor-pressure solvent (**Levap**), a medium vapor-pressure solvent (**Mevap**), a high vapor-pressure solvent (**Hevap**) and a very high vapor-pressure solvent (**HHevap**), wherein the resin and the photochromic dye are dissolved within the solvent system.

The softening agent includes a liquid softening agent. Typically, the liquid softening agent is, includes, or consists essentially of a non-volatile liquid softening agent.

In some embodiments, the softening agent further includes a solid softening agent such as a solid polymeric softening agent.

In some embodiments, the ink formulation is an ophthalmic formulation.

In some embodiments, the ink formulation is suitable for forming an ophthalmic film on an ophthalmic substrate.

In some embodiments, the resin is an ophthalmic, film-forming resin.

In some embodiments, the non-volatile content of the ink formulation is within a range of 2.5 to 15%.

In some embodiments, a first solvent weight ratio of **Hevap**, **HHevap**, and **LLevap** to the total amount of solvent **Ts** within the ink formulation,

$$(\text{Hevap} + \text{HHevap} + \text{LLevap}) / \text{Ts}$$

is at least 0.6 or 0.65 or 0.7.

In some embodiments, a relative solvent weight ratio (**RWSR**) of **LLevap** to a total **T<sub>H+HH</sub>** of **Hevap** and **HHevap**,

$$\text{LLevap} / \text{T}_{\text{H+HH}}$$

is at least 0.15:1.

In some embodiments, the ink formulation is a solvent-based or organic ink formulation, in which the solvent system is an organic solvent system. The organic solvent system may advantageously contain a low (**Levap**) and/or very low vapor-pressure (**LLevap**) solvent that together form a single organic phase.

In some embodiments, the organic solvent system may further include one or more higher vapor-pressure solvents (**Mevap** and/or **Hevap** and/or **HHevap**), the additional higher vapor-pressure solvent(s) forming, with the **Levap** and **LLevap** solvent(s), a single phase within the organic solvent system.

As used herein in the specification and in the claims section that follows, the term “at most a high vapor-pressure (**Hevap**) solvent” is meant to exclude solvents that have faster rates of evaporation than **Hevap**, in this case, **HHevap**.

Similarly, the term “at most a medium vapor-pressure (**Mevap**) solvent” is meant to exclude solvents that have faster rates of evaporation than **Mevap**, in this case, **HHevap** and **Hevap**.

Similarly, the term “at least a medium vapor-pressure (**Mevap**) solvent” is meant to exclude solvents that have slower rates of evaporation than **Mevap**, in this case, **LLevap** and **Levap**.

More particularly, the volatile liquids are divided into 5 categories, as follows:

**LLevap** < 0.1 (e.g.: TPM, DPM, EB, NMP, DMSO, ethylene glycol monobutyl ether, DPM acetate).

$0.1 \leq \text{Levap} < 0.5$  (e.g.: EEP, EP, PP, PMA, n-butyl propionate, n-butanol, amyl acetate, water).

$0.5 \leq \text{Mevap} < 0.85$  (e.g.: PM, isobutanol).

$0.85 \leq \text{Hevap} < 1.8$  (e.g.: xylene, n-butyl acetate, isobutyl acetate, methyl isobutyl ketone, isopropanol, ethanol).

$1.8 \leq \text{HHevap}$  (e.g.: toluene, methanol, n-propyl acetate, isopropyl acetate, ethyl acetate, methyl propyl ketone, methyl ethyl ketone).

The designated standard material, n-butyl acetate, is assigned a vaporization or evaporation rate of 1.0. Thus, the term “relative evaporation rate” and the like is used with reference to n-butyl acetate.

With reference now to Figure 2, Figure 2 provides a schematic block diagram of a process of treating an optical surface of an optical substrate (typically, a lens blank such as a curved lens blank) to produce a dried hardcoat layer, according to aspects of the present invention. The lens blank provided to the process may or may not have a protective hardcoat adhering thereto.

Before applying a wet photochromic layer to the optical surface of the optical substrate, the optical surface may be subjected to an optional pretreatment stage 205.

Within pretreatment stage 205, the lens blank/optical substrate may be subjected to surface preparation (optional step 206) prior to the application of the wet photochromic layer. Such surface preparation may include washing in water or in an aqueous cleaning solution, optionally followed by drying (optional step 207).

In some embodiments, the surface preparation of the lens surface includes an etching treatment.

In some embodiments, the etching treatment includes laser etching.

In some embodiments, the etching treatment includes chemical etching.

Before applying a photochromic formulation, the lens blank may be subjected to at least one surface treatment (optional step 208), e.g., an energy treatment to raise the surface energy of the optical surface.

In some embodiments, this energy treatment includes a corona treatment.

In some embodiments, this energy treatment includes a plasma treatment.

In some embodiments, this energy treatment includes an electron beam treatment.

In some embodiments, this energy treatment includes an electromagnetic (e.g., actinic) radiation treatment.

In some embodiments, this energy treatment is an electrical discharge treatment.

Figure 3 provides optional steps for the schematic block diagram of Figure 2, in which the surface treatment or pre-treatment (e.g., optional step 208) includes applying a liquid primer formulation to the exposed (lens) surface of the ophthalmic substrate to form a wet primer layer

or coating. The wet primer layer or coating is subsequently dried or otherwise cured (e.g., at step 210), to obtain a dried primer layer or coating. Exemplary treatments include oven drying, microwave, and IR.

The drying/curing of the wet primer layer formulation may be performed by any conventional curing means for producing the cured primer layer (as described hereinabove with respect to step 104, *mutatis mutandis*). The curing of the wet primer layer may advantageously be performed so as to achieve a “fully-cured” primer layer.

The liquid primer formulation may be applied using various conventional technologies (each having any of various technological disadvantages), such as spin coating, slit coating, and dip coating.

In some embodiments, and most typically, the primer is microvalved onto the exposed surface of the ophthalmic substrate, as will be described in greater detail hereinbelow.

In some embodiments, the primer pre-treatment is directed to facilitate wetting of a photochromic layer with respect to the lens surface.

In some embodiments, the primer pre-treatment is directed to facilitate adherence of a photochromic layer with respect to the lens surface.

In some embodiments, the primer is a polymeric primer.

In some embodiments, the polymeric primer is in the form of a waterborne emulsion (e.g., an acrylic emulsion).

In some embodiments, the polymeric primer is in the form of an aqueous dispersion (e.g., a polyurethane dispersion).

In some embodiments, the polymeric primer is, or includes, a UV-curable material such as UV curable oligomers, epoxy acrylates, polyester acrylates, and urethane acrylates.

In some embodiments, the polymeric primer is in the form of a solution (e.g., a polyurethane resin solution).

In some of these embodiments, the thickness and/or average thickness of the wet primer layer is at least 0.5 $\mu$ m, at least 0.8 $\mu$ m, at least 1 $\mu$ m, at least 1.5 $\mu$ m, at least 2 $\mu$ m, at least 3 $\mu$ m, at least 5 $\mu$ m, or at least 7 $\mu$ m.

In some of these embodiments, the thickness and/or average thickness of the wet primer layer is at most 80 $\mu$ m, at most 60 $\mu$ m, at most 40 $\mu$ m, and more typically, at most 25 $\mu$ m, at most 20  $\mu$ m, or at most 15 $\mu$ m.

In some embodiments, the method includes, following step 210, and before the microvalving of the photochromic dye formulation, effecting such an energy treatment (e.g., corona or plasma, or actinic radiation) to the top/exposed surface of the fully cured primer layer.

In some embodiments of these energy treatments, the energy treatment increases the surface energy of a target surface of the optical substrate by at least 2, 3, 5, 8, or 12 milliNewton/meter (mN/m).

In some of these embodiments, the energy treatment increases the surface energy of the target surface by at most 40, at most 30, at most 20, at most 17, or at most 14 mN/m.

With reference again to Figure 2, following optional pretreatment stage 205, the method comprises microvalving drops of a liquid photochromic dye formulation (step 224), typically via a microvalve, onto the optionally pre-treated lens blank/optical substrate.

As schematically provided in Figures 4A and 4B, a microvalve apparatus may be utilized to jet ink drops onto surfaces of different contours, including a convex lens surface (Figure 4A) and a concave lens surface (Figure 4B).

In some embodiments, the liquid photochromic dye formulation is microvalved directly onto the surface of the lens/lens blank/optical substrate.

In some embodiments, the liquid photochromic dye formulation is microvalved on top of a primer layer, e.g., the primer layer applied in optional surface treatment 208.

In some embodiments, the photochromic ink formulation contains at least one photochromic dye.

In some embodiments, the photochromic ink formulation is devoid of pigment.

In some embodiments, the photochromic ink formulation is devoid of photochromic pigment.

In some embodiments, the photochromic ink formulation contains at least one polymeric resin (e.g., as a binder).

In some embodiments, the obtained photochromic ink layer may be dried or otherwise cured (step 226) to produce a dried and cured photochromic ink layer.

The drying/curing of the photochromic ink layer may be performed by any conventional curing means for producing the cured photochromic layer (as described hereinabove with respect to steps 104 and 210, *mutatis mutandis*). The curing of the photochromic ink layer may advantageously be performed so as to achieve a “fully-cured” primer layer.

In some embodiments, the photochromic dye containing layer, after complete drying and curing, has a thickness or an average thickness within the range of 0.6 to 30 $\mu$ m or 1 to 20 $\mu$ m, and more typically, within a range of 1.2 to 20 $\mu$ m, 1.5 to 20 $\mu$ m, 1.5 to 15 $\mu$ m, 1.5 to 12 $\mu$ m, 1.5 to 10 $\mu$ m, 1.5 to 8 $\mu$ m, 1.5 to 6 $\mu$ m, 1.5 to 5 $\mu$ m, 1.5 to 4 $\mu$ m, 2 to 25 $\mu$ m, 2 to 15 $\mu$ m, 2 to 12 $\mu$ m, 2 to 10 $\mu$ m, 2 to 8 $\mu$ m, 2 to 6 $\mu$ m, 2.5 to 20 $\mu$ m, 2.5 to 15 $\mu$ m, 2.5 to 12 $\mu$ m, 2.5 to 8 $\mu$ m, 2.5 to 6 $\mu$ m, 1.5 to 5 $\mu$ m, 3 to 20 $\mu$ m, 3 to 15 $\mu$ m, 3 to 8 $\mu$ m, 3 to 6 $\mu$ m, 3.5 to 20 $\mu$ m, 3.5 to 12 $\mu$ m, 3.5 to 10 $\mu$ m, 3.5 to 8 $\mu$ m, or 3.5 to 6 $\mu$ m.

In some embodiments, steps 224 and 226 are repeated at least once or twice, with the identical photochromic ink or with one or more different photochromic inks (e.g., having a different color).

In some embodiments, following steps 224 and 226, an additional, non-photochromic ink layer may be applied and dried or otherwise cured (as described hereinabove, e.g., with respect to step 104, *mutatis mutandis*).

In some embodiments, the additional ink formulation contains at least one dissolved dye (e.g., a tint).

In some embodiments, the additional ink formulation is a solvent-based formulation.

The inventors have found that various hardcoat formulations may dissolve or otherwise attack the colorant containing ink layer, and more specifically, the photochromic dye containing layer formed and cured in steps 224 and 226. However, the inventors have further discovered that by applying an overcoat layer (step 228) on top of this colorant containing ink layer and effecting drying/curing (step 230) as necessary, such attack may be inhibited or appreciably mitigated.

In some embodiments, the method includes, following step 226, and before the applying of the overcoat formulation (step 228), effecting an energy treatment (e.g., any of the energy treatments described hereinabove, *mutatis mutandis*) to the top/exposed surface of the cured or fully-cured photochromic layer. This may appreciably improve the adhesion between the fully-cured photochromic layer and the overcoat layer.

In some embodiments, the first overcoat layer, as a wet layer, has a thickness or an average thickness within a range of 6 to 100 $\mu$ m, 6 to 80 $\mu$ m, 6 to 60 $\mu$ m, or 6 to 50 $\mu$ m.

In some of these embodiments, this layer has a thickness or an average thickness of at least 8 $\mu$ m, at least 12 $\mu$ m, at least 20 $\mu$ m, at least 30 $\mu$ m, or at least 40 $\mu$ m.

In some embodiments, the first overcoat layer, as a dry layer, has a thickness or an average thickness within a range of 3 to 15 $\mu$ m.

In some of these embodiments, this dry thickness or average thickness is at least 4 $\mu$ m, at least 5.5 $\mu$ m, at least 6.5 $\mu$ m, or at least 7.5 $\mu$ m.

In some of these embodiments, this dry thickness or average thickness is at most 13.5 $\mu$ m, at most 12 $\mu$ m, at most 11 $\mu$ m, or at most 10 $\mu$ m.

In some embodiments, the material of the dry or fully cured overcoat layer has a König hardness of at least 80 (seconds). More typically, this König hardness is within a range of 80 to 180, 80 to 160, 90 to 180, 100 to 160, 100 to 150, 100 to 140, 110 to 180, 110 to 160, or 110 to 150.

In some embodiments, the first overcoat layer is or contains a thermoplastic polymer.

In some embodiments, the first overcoat layer is or contains a thermoset polymer.

In some embodiments, the first overcoat formulation is a polymer emulsion.

In some embodiments, the first overcoat formulation is a polymer dispersion.

In some embodiments, the first overcoat formulation is a polymer solution.

In some embodiments, the first overcoat formulation includes an acrylic polymer.

In some embodiments, the first overcoat formulation includes a polyurethane.

In some embodiments, the first overcoat formulation includes a polyvinyl ester resin such as polyvinyl butyral and polyvinylpyrrolidone vinyl acetate copolymer .

In some embodiments, the first overcoat formulation includes epoxy resin.

In some embodiments, the material of fully cured overcoat layer includes, predominantly includes, or consists of any of the above polymers.

In some embodiments, the PVB-based overcoat formulation may be a PVB-containing aqueous dispersion, for example, as disclosed in EP3587106 (e.g., Example 1A).

In some embodiments, the method further comprises, following the drying/curing (step 230) of the overcoat layer, applying a second or additional overcoat layer on top of the dried first overcoat layer.

In some embodiments, the method further comprises drying/curing the second or additional overcoat layer.

In some embodiments, the dried second or additional overcoat layer may exhibit increased hardness with respect to the dried first overcoat layer.

In some embodiments, the dried second or additional overcoat layer may exhibit increased a lower coefficient of linear thermal expansion (CTE) with respect to the dried first overcoat layer.

In some embodiments, the method further comprises, following curing (step 226 or 228), applying a liquid (film-forming) hardcoat ("1<sup>st</sup> hardcoat" or "inner hardcoat") formulation onto the exposed optical or ophthalmic surface of the optical or ophthalmic substrate, to form a wet hardcoat layer (step 232). This may be followed by treating the wet layer to produce a dried, typically transparent hardcoat layer on the optical surface (step 234).

In some embodiments, the method includes, following step 226 or 230, and before the applying of the hardcoat formulation (step 232), effecting an energy treatment (e.g., any of the energy treatments described hereinabove, *mutatis mutandis*) to the top/exposed surface of the cured or fully-cured photochromic or overcoat layer, respectively. This may appreciably improve the adhesion between the fully-cured underlayer and the hardcoat layer.

In some embodiments, the applying of the (1<sup>st</sup>) liquid hardcoat formulation is effected by microvalving drops of the formulation onto the exposed surface of the ophthalmic substrate.

In some embodiments, the method further comprises, following curing of the 1<sup>st</sup> hardcoat layer, applying a 2<sup>nd</sup> liquid (film-forming) hardcoat (“2<sup>nd</sup> hardcoat” or “outer hardcoat”) formulation onto the exposed optical or ophthalmic surface of the optical or ophthalmic substrate, to form a wet 2<sup>nd</sup> hardcoat layer. This optional step may be followed by treating the wet layer to produce a dried, typically transparent 2<sup>nd</sup> hardcoat layer on the optical surface.

In some embodiments, the applying of the (2<sup>nd</sup>) liquid hardcoat formulation is effected by microvalving drops of the formulation onto the exposed surface of the ophthalmic substrate.

In some embodiments, the hardcoat formulation base includes one or more acrylates, methacrylates, and the like, some of which are provided below in non-exhaustive fashion: hydroxyethyl acrylate, hydroxypropyl acrylate, hydroxybutyl acrylate, hydroxy-poly(alkyleneoxy)alkyl acrylate, caprolactone acrylate, ethylene glycol diacrylate, butanediol diacrylate, hexanediol diacrylate, hexamethylene diacrylate, diethylene glycol diacrylate, and triethylene glycol diacrylate.

UV catalysts for the photo-polymerization initiation may include, by way of example, any of the following materials: benzil, benzoin, benzoin methyl ether, benzoin isobutyl ether, benzophenol, acetophenone, benzophenone, as well as mixtures thereof. One skilled in the art will readily appreciate that other suitable UV catalysts may be employed.

In some embodiments, the ophthalmic hardcoat formulation is based upon Sol-gel monomers and oligomers.

In some embodiments, the coating compositions utilized in conjunction with the present invention comprise an aqueous organic solvent mixture containing from about 10 to about 99.9 weight percent, based on the total solids of the composition, of a mixture of hydrolysis products and partial condensates of an epoxy functional silane and a tetrafunctional silane and from about 0.1 to about 30 weight percent, based on the total solids of the composition, of a crosslinking crosslinking multifunctional compound selected from the group consisting of crosslinking multifunctional carboxylic acids, crosslinking multifunctional anhydrides and combinations thereof.

Hardcoat coating compositions are well known to those skill in the art. By way of example, thermal curable coating technologies are disclosed in various patents, including the following U.S. Patents: 4,547,397, 5,385,955, and 6,538,092, and radiation curable coatings are disclosed in U.S. Patent Nos. 4,478,876 and 5,409,965.

Referring again to Figure 2, when two or more layers of hardcoat are applied to the substrate, the outermost layer will typically be the hardest. The one or more inner layers of hardcoat may be somewhat softer, and may be adapted such that there is a gradual change in physical properties (e.g., hardness, coefficient of thermal expansion, etc.), to impart improved

mechanical properties to the layered stack. This may be of particular importance if the stack includes one or more relatively soft photochromic layers, as will be developed in further detail hereinbelow. It must be emphasized that when a single hardcoat layer is applied, this layer is the “outer hardcoat”, or the “overcoat” of step 228.

In some embodiments, the outermost hardcoat layer or coating, as a wet layer, has a thickness or an average thickness within a range of 1.5 to 40 $\mu$ m, 2.5 to 40 $\mu$ m, 4 to 40 $\mu$ m, 6 to 40 $\mu$ m, 4 to 25 $\mu$ m, 6 to 25 $\mu$ m, 4 to 15 $\mu$ m, or 6 to 15 $\mu$ m.

In some embodiments, the optional at least one inner hardcoat layer or coating, as a wet layer, has a thickness or an average thickness within a range of 1 to 25 $\mu$ m or within a range of 1.5 to 20 $\mu$ m, and more typically, within a range of 1.5 to 15 $\mu$ m, 1.5 to 10 $\mu$ m, 1.5 to 7 $\mu$ m, 1.5 to 5 $\mu$ m, 2 to 10 $\mu$ m, 2 to 7 $\mu$ m, or 3 to 7 $\mu$ m.

The inner coat layer or coating, after complete drying, typically has a thickness of within the range of 0.6 to 5 $\mu$ m or 0.6 to 4 $\mu$ m, and more typically, within a range of 0.6 to 3.5 $\mu$ m, 0.6 to 3 $\mu$ m, 0.6 to 2.5 $\mu$ m, 0.8 to 2.2 $\mu$ m, 0.8 to 2.0 $\mu$ m, 0.8 to 1.8 $\mu$ m, 0.8 to 1.6 $\mu$ m, or 1.0 to 1.5 $\mu$ m.

In some embodiments, the hardcoat formulations include one or more type of nanoparticles, e.g., for increased hardness or strength. Such nanoparticles may include boron nitride, B<sub>4</sub>C, cubic BC<sub>2</sub>N, silicon carbide, crystalline alpha alumina (sapphire); aluminum oxide, silicon oxide, tin oxide, zirconium oxide, and titanium oxide.

Following drying/curing step 230 or drying/curing step 232, the method may include applying a liquid (film-forming) post-hardcoat formulation onto an optical or ophthalmic surface of an optical or ophthalmic substrate, to form a wet layer. This may be followed by treating the wet layer to produce a dried (fully-cured) transparent post-hardcoat layer on the optical surface. These steps have been described hereinabove in a general fashion.

Such post hardcoat layers may include at least one of the following functionalities:

- anti-wetting layer
- anti-reflective layer
- super hydrophobic /anti-fog layer
- super hydrophilic /anti-fog layer
- anti-glare layer
- blue light.

It will be appreciated by those of skill in the art that these post-hardcoat formulations may be applied by microvalving or inkjetting or by conventional coating processes such as spin coating and dip coating, or PVD or CVD for the extremely thin layers.

In embodiments, a microvalve coating system comprises a photochromic-ink-formulation-application station including microvalving apparatus configured to microvalve droplets of the formulation onto a target surface of an optical substrate to form a wet layer of the

photochromic ink formulation on the target surface; a drying and/or curing station configured to dry and/or cure, on the target surface, the wet layer of the photochromic formulation into a dry coating thereof; and optionally but typically, an optical-substrate transfer apparatus configured to transfer the optical substrate and the wet layer on the target surface thereof from the photochromic-ink-formulation-application station to the drying and/or curing station.

In some embodiments, the optical-substrate transfer apparatus includes at least one of a robotic arm, a gripper, a conveyor belt, and an elevator for raising or lowering an elevation of the optical substrate and the wet layer on the target surface thereof.

In some embodiments, the microvalve coating system further comprises a controller for regulating the optical-substrate-transfer apparatus such that the transfer of the optical substrate is contingent upon a detection that the wet layer has been formed on the target surface of the optical substrate at the photochromic-ink-formulation-application station.

In some embodiments, the drying and/or curing station includes at least one of a heat lamp and an oven.

In some embodiments, the drying and/or curing station includes an oven which: (i) is open when the optical substrate with the wet layer on the target surface thereof is transferred into the housing of the optical substrate with the wet layer on the target surface; and (ii) is closed, subsequent to transfer of the optical substrate to the oven, and remains closed during the drying and/curing.

In some embodiments, the system further comprises a primer application station for microvalving droplets of primer formulation onto the target surface of the optical substrate before the optical substrate is subsequently transferred to the photochromic-ink-formulation-application station.

In some embodiments, the microvalve apparatus of the photochromic-ink-formulation-application station is configured to microvalve droplets of a photochromic ink onto the target surface of an optical substrate.

In some embodiments, the microvalve coating system further comprises a surface treatment station for increasing the surface energy of the target surface of the optical substrate before microvalve-application thereon of the primer or the photochromic ink formulation.

In some embodiments, the microvalve coating system further comprises a cleaning station for subjecting the target surface of the optical substrate, before microvalve-application thereon of the primer or the photochromic ink formulation, to a cleaning process.

In some embodiments, the surface treatment station includes at least one of corona-treatment-apparatus and plasma-treatment apparatus.

In some embodiments, the hardcoating-formulation-application station includes a

reservoir of the hardcoating formulation and is configured to microvalve, onto the target surface of the optical substrate, the hardcoating formulation stored in the reservoir.

In some embodiments, the system is devoid of any dip coating apparatus.

In some embodiments, the system is devoid of any spin coating apparatus.

Figure 4 is a schematic cross-sectional view of a multi-layered optical or ophthalmic device, component or structure 400, which includes an optical or ophthalmic substrate 402 having an optical or ophthalmic construction 403 fixedly attached to a broad surface 401 of the optical or ophthalmic substrate 402. Construction 403 further includes a primer layer 440 disposed between broad surface 401 and photochromic layer 404. The thickness of photochromic layer 404 is designated as  $T_{PC}$ , while the thickness of primer layer 440 is designated as  $T_p$ . Above photochromic layer 404 may be disposed an overcoat layer 406, substantially as described hereinabove. The thickness of overcoat layer 406 is designated as  $T_{ov}$ . Above overcoat layer 406 may be disposed one or more hardcoat layers 420, according to further features of the present invention. Above hardcoat layer(s) 420, whose thickness is designated as  $T_h$ , one or more post-hardcoat layers 430 may be disposed. The entire thickness of optical construction 403 is designated as  $T_{oc}$ .

In some embodiments,  $T_p$  is within a range of 0.2 to  $3\mu\text{m}$ .

In some embodiments,  $T_p$  is at least 0.4, at least 0.6 or at least  $0.8\mu\text{m}$ .

In some embodiments,  $T_p$  is at most  $2.5\mu\text{m}$ , at most  $2\mu\text{m}$ , at most  $1.6\mu\text{m}$ , at most  $1.3\mu\text{m}$ , or at most  $1.0\mu\text{m}$ .

In some embodiments,  $T_{PC}$  is within a range of 1 to  $10\mu\text{m}$ .

In some embodiments,  $T_{PC}$  is within a range of 1.2 to  $8\mu\text{m}$ .

In some embodiments,  $T_{PC}$  is at least 1.5, at least 1.8, at least 2.0, at least 2.5, or at least  $3\mu\text{m}$ .

In some embodiments,  $T_{PC}$  is at most  $7\mu\text{m}$ , at most  $6\mu\text{m}$ , at most  $5\mu\text{m}$ , at most  $4.5\mu\text{m}$ , or at most  $4\mu\text{m}$ .

In some embodiments,  $T_{ov}$  is at least 4, at least 6, at least 7, or at least  $7.5\mu\text{m}$ .

In some embodiments,  $T_{ov}$  is at most  $18\mu\text{m}$ , at most  $15\mu\text{m}$ , at most  $13\mu\text{m}$ , at most  $12\mu\text{m}$ , or at most  $11\mu\text{m}$ .

In some embodiments, the fully-cured hardcoat layer has at least one of a local thickness  $T_{h-l}$  and an average thickness  $T_{h-a}$  of at least  $1.2\mu\text{m}$ , at least  $1.5\mu\text{m}$ , at least  $1.8\mu\text{m}$ , at least  $2\mu\text{m}$ , at least  $2.5\mu\text{m}$ , and more typically, at least  $3\mu\text{m}$  or at least  $3.5\mu\text{m}$ .

In some embodiments, at least one of  $T_{h-l}$  and  $T_{h-a}$  is at most  $8\mu\text{m}$ , at most  $6\mu\text{m}$ , or at most  $4.5\mu\text{m}$ , at most  $3.5\mu\text{m}$ ,

When applied directly on the overcoat layer, the fully-cured hardcoat may have a thickness or an average thickness within a range of 1.2 to 3.5 $\mu\text{m}$ , 1.5 to 3.5 $\mu\text{m}$ , or 1.8 to 3 $\mu\text{m}$ . More typically, the thickness or average thickness is at most 2.7 $\mu\text{m}$ , at most 2.4 $\mu\text{m}$ , at most 2.2 $\mu\text{m}$ , or at most 2  $\mu\text{m}$ .

In some embodiments, at least one of **Th-I** and **Th-a** is at most 8 $\mu\text{m}$ , at most 6 $\mu\text{m}$ , at most 4.5 $\mu\text{m}$ , at most 3.5 $\mu\text{m}$ , at most 3 $\mu\text{m}$ , at most 2.7 $\mu\text{m}$ , at most 2.4 $\mu\text{m}$ , or at most 2.2 $\mu\text{m}$ .

With regard to the entire thickness **Toc** of optical construction 403, in some embodiments, the dry (cured) optical construction has an average thickness within the range of 1 to 50 $\mu\text{m}$ , 3 to 50 $\mu\text{m}$ , 5 to 50 $\mu\text{m}$ , or 8 to 50 $\mu\text{m}$ .

In some embodiments, **Toc** is at least 10 $\mu\text{m}$ , at least 12 $\mu\text{m}$ , or at least 15 $\mu\text{m}$ .

In some embodiments, **Toc** is at most 40 $\mu\text{m}$ , at most 30 $\mu\text{m}$ , at most 25 $\mu\text{m}$ , at most 20 $\mu\text{m}$ , or at most 16 $\mu\text{m}$ .

Fig. 5 schematically illustrates selected steps of a process for coating an optical or ophthalmic substrate (OS) **1100**, for example a lens blank, using a coating system **1300**.

Examples of OS **1100** (e.g. to apply thereon one or more coating using any teaching or combination of teachings disclosed herein) include but are not limited to: (i) eyeglass lenses; (ii) Single-Vision Lenses; (iii) Multifocal Lenses; (iv) Anti-fatigue lenses (e.g. including a single-vision prescription and a boost of magnification at the bottom of the lens); (v) Progressive lenses (e.g. designed to correct for multiple viewing distances—including far, intermediate and near—in one lens); (vi) Prism Lenses; (vii) Spherical lenses; (viii) Cylindrical lenses. Other examples of OS **1110** include lenses of a virtual-reality (VR) device including but not limited to VR glasses or VR goggles.

Element **1110** schematically represents a target surface of an optical substrate **1100** to be coated with at least one dried layer, e.g. multiple dried layers stacked directly or indirectly on each other. For example, an optical substrate (OS) **1110** may correspond to optical or ophthalmic device, component or structure **400** (e.g. an uncoated version or partially uncoated version thereof). For example, the target surface **1110** may correspond to surface **401**, or to any other surface of any other layer of Figure 4.

For example, the target surface **1110** may correspond to the ‘outward-facing surface’, i.e. that which will face away from the wearer of the glasses of an eyeglass lens.

Target surface **1110**, before being modified by coating system **1300**, may be uncoated or may be pre-coated, e.g. before ‘delivery’. In contrast, coated substrate OS **1100’** has a coated version of target surface **1110** – i.e. after a coating is applied by coating system **1300**.

In embodiments, an optical coating system **1300** may be employed to provide ‘customization’ of optical articles-of-manufacturing (e.g. eyeglasses). For example, optical

coating system **1300** may be deployed in a factory or in a store-front, e.g., of an optometrist. For example, optical coating system **1300** may include, or may be in communication with, a digital computer (not shown), which stores and/or includes directives for producing a customized optical article-of-manufacturing.

In one non-limiting use-case, a customer having a certain optical prescription may require one or more of, e.g. any combination of: (i) specific tint or target color – i.e. to customize her/lens to a specific color; and/or (ii) a specific physical or characteristic such as, e.g. abrasion resistance; and/or (iii) a presence or absence of photochromatic features; and/or (iv) a desired glossiness; and/or (v) a desired presence or absence of varnish.

The manufacturing of the lens geometries, e.g. to satisfy a certain optical prescription and/or shape, may optionally be carried out ‘off site’ in a different location from where the coating system **1300** is deployed.

Since the possible combinations of articles-of-manufacturing could be very large such as many types of lens geometries, multiple types of ‘color features’ for coating a lens, or target colors to coat the lens, target digital pixel-patterns of lenses, etc., it may not be practical to maintain an inventory of ‘every possibility.’

Instead, it may be desirable to maintain a supply **1120** of multiple types of ‘raw material’ substrates **1100** based on lens geometry. Thus, a specific workpiece such as OS **1100** may be selected from a plurality of candidates, which can optionally be stored in a digital computer, according to specified geometric properties such as, for example g. properties expressed as an optical prescription. An ‘input’ OS **1100** may be selected by rejecting some candidate in favor of a ‘preferred candidate’ OS **1100** whose geometric properties best match required lens-geometry and/or refractive index and/or multi-focal directive and/or astigmatism directive and/or optical prescription data.

The coated OS **1100'**, such as an eyeglass blank or an eyeglass lens can be cut and/or installed into eyeglass frames in a lens-cutting and/or glasses-frame installing apparatus **1200**.

OS **1100**, in some embodiments, is rigid – e.g. having an average thickness (alternatively or additionally, a thickness in at least one location of OS **1100**) that is at least 0.5 mm or at least 1 mm or at least 2 mm or at least 3 mm).

As will be discussed below, a coating system **1300** in various embodiments apply one or more dried layers of optionally transparent material dried layer of material or multiple dried layers onto or over surface **1110** of OS **1100**.

The combination of: (A) operating parameter(s) of coating system **1300** and/or (B) physical and/or chemical properties of materials (e.g. viscosity and/or fraction of solids and/or surface-energy, employed by any implementation or embodiment of coating system **1300** may be

such that the layers, i.e. dried and/or transparent layers produced on or over surface **1110** of OS **1100**, have one or more specific properties.

Such properties include, but are not limited to, (i) thickness of a particular dried transparent layer or ratios between different transparent layer ratios (ii) area over which the transparent layer or a convex subportion thereof is continuous over the entirety of the area of convex subportion thereof; (iii) color and/or optical density of any dried layer; (iv) mechanical properties of any dried layer or combination of layer(s). Thus, system **1300** may be configured to manufacture on surface **1110** of OS **1100** to obtain any property or combination of properties of wet or dried layers disclosed herein.

As will be discussed below, operating parameters of coating system **1300** or any one or more of its components, including components controllable, e.g., by controller **1250** (not shown in Fig. 5) can include, without limitation: (i) parameters for microvalving or inkjetting drops (or, equivalently as used herein: droplets) such as, for example, drop velocity, drop-deposition frequency, drop size and/or volume, spacing between droplets, or any other operating parameter for depositing drop or droplets, drop or droplet ejection-speed, and gap-distance between a nozzle of a microvalve or inkjet device and target surface **1110**; (ii) drying time or drying temperature or drying intensity or power or any other parameter related to drying of a wet layer such as, for example, oven temperature, parameters of convective and/or radiative drying such as, for example, UV intensity; (iii) relative motion between any nozzle for delivering drops or droplets and target surface **1110**; (iv) properties related to treating surface **1110** of OS **1100**, e.g. to obtain a desired surface-energy or an energy in a certain range; (v) selection of a formulation, or a container, cartridge or reservoir of the formulation, from a plurality of candidates and/or mixing of a formulation; and ventilation operating parameters.

In different embodiments, the term ‘apparatus’ may refer to a specific station (e.g. drying station and/or wet layer-application station for any wet layer). Thus, any reference to ‘apparatus’ may also be taken as (i.e. in embodiments of the invention) a ‘station’.

In various embodiments, the components of optical coating system **1300** are configured and/or arranged to perform any method described here in (e.g. reference to Figures 1-3 – all steps or any combination of step(s) to provide any feature of combination of feature(s) – not all steps are required.

The resulting coated OS **1100'** may include any dry layer or combination of layers or feature(s) thereof or combination(s) thereof taught with reference to Figure 4 (not all layers are required) – the layers produced and properties thereof (e.g. within the framework of Figure 4) are according to the specific elements (and their operating parameter(s) and formulation(s)) of a

specific implementation of coating system **1300** - we note various versions of system **1300** are described herein.

Various examples and/or embodiments of coating systems **1300** and/or processes related to coating systems are schematically presented in Figs. 6A-6C, 7A-7B, 8, 9, 10A-10C, and 11 as block diagrams and/or flow-diagrams illustrating various systems and methods according to various embodiments of the disclosure.

Fig. 6A shows a block diagram of an exemplary coating system **1300A**. The coating system **1300A** can include any one or more (or all) of (i) a hardcoating-formulation application apparatus **1350** for applying a coating or layer of a hardcoating formulation e.g. by microvalving, (ii) hardcoat-drying and/curing apparatus **1370** for drying and/or curing a wet layer of a hardcoat formulation, (iii) selection and/or transfer apparatus **1330**, and a (IV) controller **1250**. In some embodiments, the hardcoat formulation comprises an ink, e.g., for tinting and/or photochromic tinting, and/or an electrochromic ink. The wet layer can be 'thin', characterized by having a thickness of at most 100 or 90 or 75 or 50 or 25 or 20 or 15 or 10 microns.

Fig. 6B shows a block diagram of another exemplary coating system **1300B**. The coating system **1300B** can include any one or more (or all) of (i) a microvalve-based coating apparatus **1900** for coating a surface of an optical substrate **1100**, configured, for example, to coat on the surface **1110** of optical substrate **1100** by microvalving liquid drops to form one or more thin layers of a formulation. Such a thin layer can be characterized by having a thickness of at most 100 or 90 or 75 or 50 or 25 or 20 or 15 or 10 microns. (ii) drying and/or curing apparatus **1910**, (iii) selection and/or transfer apparatus **1330**, and (iv) a controller **1250**. In an example, one or more wet layers applied by microvalve-based coating apparatus **1900** are subjected to a drying and/or curing process by drying and/or curing apparatus **1910**. Examples of the 'formulations' which can be applied by microvalve-based coating apparatus **1900** are: (i) hard-coating formulations which may be microvalved to produce a layer of the hard-coating formulation, (ii) ink-formulations, e.g., for tinting or photochromic and/or electrochromic ink to produce a layer of the ink formulation; (iii) surface-energy-increasing formulations which may be microvalved to produce a layer of the surface-energy-increasing formulation so as to increase the surface energy of the target surface **1110** of the optical substrate **1100**.

In embodiments related to Fig. 6B, one of more of the features can be provided by the coating system **1300B** (or elements thereof): (i) microvalve-based coating apparatus **1900**, forms by microvalving drops onto target surface **1110**, one or more continuous wet layers, which may be stacked by drying a preceding layer; (ii) microvalve-based coating apparatus **1900** for forming, by microvalving drops onto the target surface **1110**, a continuous wet layer that is thin – characterized by having a thickness of at most 100 or 90 or 75 or 50 or 25 or 20 or 15 or 10

microns; and (iii) drying and/curing apparatus **1910** which transforms continuous wet layer into a continuous dry layer for one layer or for multiple stacked layers.

The skilled artisan will appreciate that microvalve-based coating apparatus **1900** may deliver only one such layer or may deliver a plurality of such layers such that layers are stacked on each other. For example, it can be that a first layer may first be dried by the drying and/or curing apparatus **1910** before a second layer is applied directly or indirectly over the first layer.

The exemplary coating system **1300C** of Fig. 6C is a specific example of coating system **1300B** of Fig. 6B where multiple layers are stacked on each other on upper target surface **1110** of optical substrate **1100**. At least one of such layers is produced by microvalving drops – e.g. by microvalve based coating apparatus **1900** or **1920**.

Reference is now made to Fig. 7A. In the example of Fig. 7A, an optical substrate **1100** is first treated by surface-energy-increasing apparatus **1310** to increase the surface energy of the target surface **1110** before coated by the coating system **1300A** or any other coating system **1300** disclosed herein to apply one or more layers, e.g., with a hardcoating formulation.

Fig. 7B is another example of a coding system where optical substrate **1100** is first treated by surface-energy-increasing apparatus, and subsequently coated by hardcoating-formulation application apparatus **1350** to apply a wet layer and/or coating of a hardcoating formulation. This wet layer and/or coating of a hardcoating formulation is subsequently dried and/or cured by hardcoat-drying and/or curing apparatus **1370**, to yield coated optical substrate **1100'**. The system of Fig. 7B may also including (i) selection and/or transfer apparatus **1330** and/or (ii) a controller **1250**.

According to embodiments, a coating system **1300** may include any one or more of the following components:

One or more controllers **1250**: for simplicity, only a single controller **1250** is shown in the various drawings. A controller **1250** can regulate operating parameters of any other element of a coating system **1300**, including, but not exhaustively: microvalving apparatus, drying apparatus, ink-jet apparatus, transfer apparatus, or any other apparatus or combination if present. The controller **1250** may be part of and/or be located in the coating system **1300** or in any of the components, and/or may be located separately and/or remotely. Controller **1250** may include any electrical and/or electronic components required to perform its function of controlling any component or combination of components.

In some embodiments of the invention, any coating system **1300** disclosed herein may include data-acquisition and/or monitoring apparatus **1430** such as, for example, imaging and/or inspection components. A controller **1250** may directly or indirectly receive data from such data-acquisition and/or monitoring apparatus **1430**.

Hardcoating-formulation application apparatus **1350** microvalves drops of hardcoat formulation onto the target surface **1110** of an OS **1100** in order to produce on the surface **1110** a wet layer of hard coat formulation from the microvalved droplets of hardcoat formulation. The hardcoating apparatus **1350** can be in communication with and/or loaded with a hardcoating formulation. In any of the embodiments of the coating system, a formulation, including without limitation a hardcoating formulation, can be disposed within a cartridge or any other container or reservoir.

The hardcoating formulation employed by the hardcoating apparatus **1350** may be in accordance with any hardcoat formulation teaching disclosed herein or any combinations of the teachings. As already disclosed hereinabove, the hardcoating formulation employed by a microvalve-based apparatus, e.g., microvalving apparatus **1900**, can optionally also be an ink.

In various embodiments, hardcoating apparatus **1350** may be configured and/or regulated by the controller **1250** to produce a wet layer of hardcoat formulation having specific properties. For example, the wet layer can comprise a sub-100 $\mu$  wet layer of hardcoat formulation. For example, the wet layer can have a thickness of at most 90 microns or at most 75 microns or at most 50 microns or at most 25 microns or at most 20 microns or at most 15 microns or at most 10 microns. For example, the wet layer may be continuous at least over a certain area (e.g. at least over a convex region having a specific area – e.g. at least 1 cm<sup>2</sup> or at least 2 cm<sup>2</sup> or at least 4 cm<sup>2</sup> or at least 8 cm<sup>2</sup>).

In various embodiments, apparatus **1350** is configured, e.g., by controller **1250** and/or by formulation properties to perform step **102** of Figure 1 and/or step **224** of Figure 2.

Hardcoat-drying and/or curing apparatus **1370** can be provided and configured for applying thermal energy to a wet layer of hardcoat formulation such as that produced by hardcoating apparatus **1350** and having a thickness or any other properties taught herein, to convert this wet layer in hardcoat formulation into a dried hardcoat layer having any property disclosed herein. In various embodiments, the hardcoating apparatus **1350** is configured, e.g., by the controller **1250** and/or by formulation properties to perform step **102** of Figure 1 and/or step **224** of Figure 2.

Selection and/or transfer apparatus **1330** for selecting and/or providing relative motion of OS **1110** relative to any apparatus and/or unit and/or station of **1300** or component thereof. This ‘relative motion’ may transport, e.g., by translation and/or rotational motion, the OS **1100** or portion thereof and/or any apparatus and/or component and/or station of the coating system **1300** relative to the OS **1100**.

In different embodiments, selection and/or transfer apparatus **1330** may be controlled at least in part by the controller **1250**, e.g. to achieve a directive stored in a digital computer, such as, for example a target property of hardcoating layer.

In various embodiments, selection and/or transfer apparatus **1330** may include one or more of: a robotic arm, a gripper, a conveyer belt, and an elevator for raising or lowering an elevation of the optical substrate and the wet layer on the target surface thereof.

Selection and/or transfer apparatus **1330** may be configured for such relative motion between components of coating system **1300** and/or for selecting an OS **1110** from a plurality of candidates according to a directive in computer storage and/or read by a digital computer such as, for example, an optical prescription.

Microvalve-based coating apparatus **1900** or **1920**: any wet layer disclosed herein may be applied by microvalving apparatus **1900**, which in embodiments can be controlled by the controllers **1250**, as in, for example, step 102 of Figure 1. The operating parameters of **1900** may depend on the specific layer to be formed or the formulation from which this layer is produced. Thus, apparatus **1900** may, in different embodiments, perform step 224 of Figure 2 and/or 228 of Figure 2 and/or 310 of Figure 2A and/or 324 of Figure 3 and/or step 228 of Figure 3.

A coating system may include a single instance of microvalving apparatus **1900** or **1920** configured to operate in accordance with multiple sets of operating parameters depending on the wet layer to be dried/converted into a dry layer.

Any dried layer disclosed or claimed herein, for example a dried layer produced by any method or system disclosed herein, e.g., by step 104 of Figure 1 or step 210/310 of Figure 2/3 or step 226/326 of Figure 2/3 or step 230/330 of Figure 2/3 or step 234/334 of Figure 2/4 and/or produced by element **1370** or **1910** or **1420** or **1530** or element **1630** or element **1650** or element **1670**) may be considered continuous and/or thin as the terms are defined herein.

A ‘continuous’ dried layer is one that is continuous over an entirety of a virtual convex-region as schematically illustrated, for example, in Fig. 12D, where region **1962**, region **1966**, and region **1968** are examples of convex regions while region **1964** is a counter-example. In examples, the area of a convex-region of target surface **1110** may be, in different embodiments, at least 0.5 cm<sup>2</sup> or at least 1 cm<sup>2</sup> or at least 2 cm<sup>2</sup> or at least 4 cm<sup>2</sup> or at least 8 cm<sup>2</sup> or at least 10 cm<sup>2</sup> or at least 20 cm<sup>2</sup>).

The boundaries of the region are ‘virtual’ rather than any physical boundaries – thus, the term ‘convex region’ refers to the shape of these ‘virtual’ boundaries rather than to any geometric property of the physical topography of target surface **1110** of optical substrate **1100**.

Thus, as shown in Figs. 12B and 12C, even when topographically surface **1100** is completely concave as in Fig. 12C, it is possible to define thereupon, by defined/virtual boundaries, a convex-portion or convex-region within the topographically-concave surface **1100**.

A thickness of a 'thin' dried layer is at most 20 microns or at most 15 microns or at most 10 microns or 5 microns or at most 3 microns or at most 1 micron.

In any embodiment disclosed herein, any 'dried layer' formed from a 'wet layer formed by microvalved-drops' is sourced at least 75% wt/wt or at least 80% wt/wt or at least 90% wt/wt from the microvalved droplets.

In any embodiment disclosed herein, any 'dried layer' produced from a 'wet layer formed by drops primarily in the [ $r$  mm,  $s$  mm] ( $r$  and  $s$  are both positive numbers, mm is millimeters) range' is a dried layer that is sourced at least 75% wt/wt or at least 80% wt/wt or at least 90% wt/wt from drops (i.e. to produce the precursor wet layer which is then dried) whose width is both at least  $r$  mm and at most  $s$  mm. In different embodiments, any dried layer disclosed herein is formed primarily from drops in the [0.1 mm, 3 mm] range.

In various embodiments, any dried layer disclosed herein is formed primarily from drops in the [0.1 mm, 2 mm] range. In different embodiments, any dried layer disclosed herein is formed primarily from drops in the [0.1 mm, 1.5 mm] range. In different embodiments, any dried layer disclosed herein is formed primarily from drops in the [0.1 mm, 1 mm] range. In different embodiments, any dried layer disclosed herein is formed primarily from drops in the [0.01 mm, 1 mm] range. In different embodiments, any dried layer disclosed herein is formed primarily from drops in the [0.15 mm, 3 mm] range. In different embodiments, any dried layer disclosed herein is formed primarily from drops in the [0.2 mm, 1 mm] range.

Alternatively or additionally, multiple instances of **1900** or **1920** may be provided, each for drying a different wet layer of formulation and each operating according to different operating parameters.

(A) A drying and/or curing apparatus **1910** can include, in different implementations, an oven and/or UV apparatus or other element for converting a wet layer of formulation into a dried layer, including, optionally, a transparent layer. The operating parameters of the drying and/or curing apparatus **1910** depend upon the specific formulation and its properties. For example, for a hardcoating formulation, a drying temperature and/or energy and/or duration required/employed may exceed that required/employed for a 'primer formulation.' Any coating system **1300** may include a single **1910** or multiple drying and/or curing apparatus **1910** and the operating parameter(s) thereof depend on the formulation and/or structure of the specific wet layer to be converted into a dry layer.

In various embodiments, a drying and/or curing apparatus **1910** can be configured to perform step 104 of Figure 1 and/or step 207 of Figure 2 and/or step 210 of Figure 2 and/or step 226 of Figure 2 and/or step 230 of Figure 2 and/or step 234 of Figure 2 and/or step 320 of Figure 2A and/or step 307 of Figure 3 and/or step 310 of Figure 3 and/or step 326 of Figure 3 and/or step 330 of Figure 3 and/or step 334 of Figure 3.

(B) A surface-energy-increasing apparatus **1310**, as shown in further detail in Fig. 9, can be provided for increasing a surface energy of a target surface **1110** of the optical substrate **1100**. In various embodiments, surface-energy-increasing apparatus **1310** operates to increase the surface energy of target surface **1110** of OS **1100** by at least 2 mN/m, or at least 3 mN/m, or at least 5 mN/m, or at least 8 mN/m, or at least 12 mN/m. Alternative or additionally, the surface-energy-increasing apparatus **1310** operates to increase the surface energy of target surface **1110** of OS **1100** by at most 40 mN/m, or at most 30 mN/m, or at most 20 mN/m, or at most 17 mN/m, or at most 14 mN/m. Fig. 7C-7E illustrate non-limiting examples of coating systems **1300** that include surface-energy-increasing apparatus **1310**. In different examples, as shown in the block diagram of Fig. 9, surface-energy-increasing apparatus **1310** includes plasma-treatment apparatus **1501A** and/or corona-treatment apparatus **1510B** and/or electron-beam apparatus **1510C** and/or electron-discharge apparatus **1510D**. Alternatively or additionally, apparatus **1310** includes (i) a drop- and/or droplet-deposition device **1520** (e.g. microvalve or inkjet loaded or in fluid communication with appropriate surface-energy-increasing formulation according to any of the teachings herein and (ii) a drying and/or curing apparatus **1530** operating at lower power and/or lower temperature and/or lower duration than that for drying the wet hardcoating layer, e.g., because of the wet layer of the surface-energy-increasing formulation. In various embodiments, apparatus **1310** is configured to perform step **208** of Figure 2 and/or **308** of Figure 3. Alternatively or additionally, apparatus **1520** (i.e. any instance thereof – if present) is configured to perform step **310** of Figure 2A.

(C) With respect to the microvalve application apparatus **1490** and additional drying and/or curing apparatus **1420** of Fig. 8, there may be more than one microvalve based layer-application apparatus. Similarly, there may be more than one drying apparatus as discussed elsewhere.

Still referring to Fig. 8, any coating system **1300** disclosed herein may include any of the following in any combination:

(i) Cleaning apparatus **1440** can be provided to treat the target surface **1110** of the optical substrate **1100**, e.g., for surface-cleaning. For example, the cleaning apparatus **1440** can be configured to apply a washing solution and/or soap and/or a surfactant to the target surface **1110** of the optical substrate **1100**. For example, the cleaning apparatus **1440** can be configured to dry

an applied cleaning fluid and/or to subject the target surface **1110** to a dust-removal process. For example, the cleaning apparatus **1440** can treat the target surface **1110** before the target surface **1110** is subsequently subjected to a surface-energy-increasing process (e.g. by the apparatus **1310** or before the target surface **1110** is targeted for coating by any of the coating apparatuses disclosed herein.

(ii) Additional drying and/or curing apparatus(es) **1420** – for example, in addition to **1370** or **1910**. For example, multiple wet coatings may be applied to target surface **1110** of optical substrate **1100**. For example, a first wet coating or coating-layer may be dried and/or curried by a first drying and/or curing apparatus (e.g. **1370** or **1910**) and a second wet coating or coating-layer may be dried by element **1420**.

(iii) Ventilation apparatus **1450**;

(iv) Housing **1442**;

(v) Microvalve-based additional-layer Application Apparatus(es) **1490** – as noted above, there may be more than one microvalve based layer-application; and

(vi) Selection and/or transfer apparatus **1330** (e.g. for substrate and/or solvent and/or cartridge and/or other apparatus).

Figs. 10A-10C and 11 schematically illustrate non-limiting examples of operating respective exemplary coating systems **1300** comprising one or more ovens for drying and/or curing a wet coating on an optical substrate **1100**.

Fig. 10A illustrates an exemplary operating process as follows:

(i) A first microvalve apparatus **1610** in communication with and/or loaded with surface-energy-increasing formulation is provided for increasing the surface energy of target surface **1110** of an optical substrate **1100** so that drops that are microvalved to the surface **1110** collectively form a wet coating of the surface-energy-increasing formulation on the target surface **1110**;

(ii) A first oven **1630** is provided, to operate a drying process at a ‘low’ temperature and/or short duration – i.e. for a drying process of relative ‘low’ duration) in order. to dry the wet coating delivered by microvalve apparatus **1610**;

(iii) A second microvalve apparatus **1640** is provided for applying a second wet coating by microvalving drops of a second formulation – for example, a hardcoating – onto the target surface **1110** after the wet coating of the surface-energy-increasing formulation is dried by the first oven **1630**; and

(iv) a second oven **1650** is provided for drying and/or curing the wet coating of the wet coating of the second formulation.

The example of Fig. 10B shows a setup comprising a single oven **1670** rather than multiple ovens. A first transfer of the optical substrate **1100** is made into the single oven **1670**

for drying/curing the wet coating from the microvalve apparatus **1610**. A first transfer is made out of the single oven **1670** after the first drying/curing process. A second transfer is made into the single oven **1670** to dry or cure the wet coating from second microvalve apparatus **1640**. The requisite movement of substrate **1100** may be performed at least in part by the optical-substrate transfer apparatus **1602** and at least some of the movements can be made automatically or robotically.

Fig. 10C shows a third setup in which the coating is performed by an ink-jet apparatus **1690** instead of a microvalve apparatus. The setup and process are otherwise the same as that shown in Fig. 10A.

Fig. 11 shows a fourth setup similar to that of Fig. 7B with the addition of an ink-formulation apparatus **1646** and an ink-layer drying and/or curing apparatus(s) **1420**.

With reference now to Figs. 13A, 13B, 14, 15 and 16, Fig. 13A shows a cross-sectional side view, and Fig. 13B shows a top perspective view, of a virtual two-dimensional projection **1800** of a curved surface **1110** of an exemplary optical substrate **1100**. In embodiments, a coating system, such as any one of the coating systems **1300** disclosed herein comprising a controller **1250**, can be configured to microvalve drops with a constant density in terms of volume of formulation per unit of area of the two-dimensional projection **1800**. The term 'constant density' as used herein can mean exactly constant, or alternatively can mean within  $\pm 10\%$ , or within  $\pm 5\%$ , or within  $\pm 2\%$ , or within  $\pm 1\%$  of a mean value of the 'density', i.e., the volume of formulation per unit of area of the two-dimensional projection, ratio for the entirety of two-dimensional projection. The constant density or, in the alternative, the density within one of the given ranges from the mean, can be measured in a small area of the two-dimensional projection such as, for example, any subdivision of the two-dimensional projection **1800** having an area of 5% or more of an area of the projection **1800**.

The applied formulation can include any one or more of the inks and/or coating formulations disclosed herein. In some embodiments, the formulation is selected, *inter alia*, for physical characteristics that make the formulation suitable for being deposited on curved surfaces in the manner described here.

The term 'configured' in the foregoing should be understood as including 'programmed' and/or 'programmable', i.e., that the controller **1250** is so programmed or programmable to control the microvalving apparatus accordingly.

In some embodiments, the controller **1250** can be programmed or programmable to generate the two-dimensional projection **1800** and/or to calculate or select a target value and/or mean value of the ratio of the volume of formulation per unit of area of the two-dimensional projection **1800**.

Application of drops **175** of the formulation by a microvalving apparatus **1610** in a constant density vis-à-vis the two-dimensional projection is shown schematically in Fig. 14, although for the sake of clarity it should be noted again that the two-dimensional projection is a virtual one. The drops **175** are actually applied to the curved surface **1100**, albeit being applied in a density or, equivalently, frequency, determined by the area of the two-dimensional projection **1800**. As one can understand from the schematically illustrated geometry, the surface area of the curved surface **1110** is larger than the two-dimensional projection. Furthermore, the divergence of the area of the curved surface **1110** from that of the two-dimensional projection **1800** is larger in peripheral sections of the optical substrate **1100** than in central areas for the single-vision convex lens surface shown in the non-limiting example of Figs. 13A-14. As is known, the degree of divergence of the area of the curved surface **1110** from that of the two-dimensional projection **1800** can be determined by the curve geometry of the curved surface, e.g., from curve geometry parameters such as the sagitta **180** of the surface **1110**, the radius in the case of a spherical curve, and so on. Moreover, the actual density, i.e. the volume of formulation actually applied on the actual curved surface **1110** per unit of area of the curved surface **1110**, is, typically, inversely proportional to the ratio of the area of the curved surface **1110** to the area of the two-dimensional projection, and this applies to any subdivision of the surface **1110** as well.

Accordingly, in some embodiments, depositing the formulation in a manner or distribution suitable to the particular formulation and curve geometry can be accomplished without requiring the application process to take into account the curve geometry when selecting or calculating a density of the application. Moreover, in some embodiments, the application of the formulation can cover an area greater than the surface of the optical substrate without requiring the application process to take into account other geometric parameters, such as the diameter or shape of the optical substrate.

Fig. 15 schematically shows an annular section **1150** at the periphery of an exemplary optical substrate **1100**, which can be useful for characterizing the divergence of the area of the curved surface **1110** of the optical substrate **1100** from the corresponding area of the two-dimensional projection **1800**, as well as for characterizing the reduced actual density on the actual curved surface **1110** as a function of distance from the center. In this non-limiting example, the annular section **1150** describes the area characterized by falling between 90% and 100% of the distance from a centroid of the optical substrate **1100** to the edge **1151**. In an exemplary embodiment, the microvalving of the drops **175** of the formulation is controlled by the controller **1250** such that a ratio of a mean volume of formulation applied per unit of area of the curved surface **1110** in the outer annulus **1150** characterized by lying between 90% and 100% of a distance from a centroid of the curved surface **1110** and the perimeter **1151**, is

typically between 0.6 and 0.97 or 0.6 and 0.96, or 0.6 and 0.94 times a maximum ratio of a volume of formulation applied per unit of area of the curved surface **1100**.

Referring now to Fig. 16, a virtual tangent line **1111** (or plane) is drawn at point (x,y) on the curved surface **1110** of the optical substrate **1100**. The tangent line can be used to characterize the angle  $\alpha$  of curved surface **1110**, relative to the horizontal, and to describe the localized divergence of the area of the actual curved surface **1110** from the corresponding localized portion of the virtual two-dimensional projection **1800**. In embodiments, the angle  $\alpha$  can be between 5° and 50°, or between 10° and 40°, or between 5° and 20°, or between 20° and 50°, or within any intervening range between 5° and 50°. In embodiments, the microvalving of the drops **175** of the formulation is such that a ratio of a mean volume of formulation applied per unit of area of the curved surface **1110** at a given point on the surface **1110**, is equal to a reduction factor times a maximum ratio of a volume of formulation applied per unit of area at any point on the surface **1100**, said reduction factor being equal to a cosine of the acute angle  $\alpha$  formed between (i) a plane or line **1111** that is tangent to the curved surface **1110** at said given point and (ii) a horizontal plane.

All mentions of a horizontal plane herein refer to a plane horizontal to a floor, and tangent planes or angles refer to planes or angles when the optical substrate is at rest on a horizontal surface.

In a first example, an optical substrate **1100** such as a lens blank has a front surface characterized by a base curve of 6.00 diopter. The lens blank has a diameter of 60mm and a SAG number of 5.25mm. A virtual tangent line **1111** (or plane) drawn at a point on the edge of the curved surface **1110** forms an angle  $\alpha$  of 19.9° relative to the horizontal plane. The divergence of the area of the curved surface **1110** from that of the two-dimensional projection **1800** is such that at the point on the perimeter **1151** of the curved surface **1110**, the area of the curved surface **1110** is 6.3% larger than at the corresponding point on the two-dimensional projection **1800**. The area of outer annulus **1150** characterized by lying between 90% and 100% of a distance from the centroid of the curved surface **1110** and the perimeter **1151** is proportionally 5.6% to 5.7% larger than the corresponding outer annulus on the two-dimensional projection **1800** than is an inner region characterized by lying between 0% and 10% of a distance from the centroid of the curved surface **1110** and the perimeter **1151** with respect to a corresponding inner region on the two-dimensional projection **1800**.

In a second example, an optical substrate **1100** such as a lens blank has a front surface characterized by a base curve of 4.00 diopter. The lens blank has a diameter of 80mm and a SAG number of 6.2mm. A virtual tangent line **1111** (or plane) drawn at a point on the edge of the curved surface **1110** forms an angle  $\alpha$  of 17.6° relative to the horizontal plane. The divergence of

the area of the curved surface **1110** from that of the two-dimensional projection **1800** is such that at the point on the perimeter **1151** of the curved surface **1110**, the area of the curved surface **1110** is 4.9% larger than at the corresponding point on the two-dimensional projection **1800**. The area of outer annulus **1150** characterized by lying between 90% and 100% of a distance from the centroid of the curved surface **1110** and the perimeter **1151** is proportionally 4.4% larger than the corresponding outer annulus on the two-dimensional projection **1800** than is an inner region characterized by lying between 0% and 10% of a distance from the centroid of the curved surface **1110** and the perimeter **1151** with respect to a corresponding inner region on the two-dimensional projection **1800**.

In a third example, an optical substrate **1100** such as a lens blank has a front surface characterized by a base curve of 10.00 diopter. The lens blank has a diameter of 70mm and a SAG number of 13.2mm. A virtual tangent line **1111** (or plane) drawn at a point on the edge of the curved surface **1110** forms an angle  $\alpha$  of 41.3° relative to the horizontal plane. The divergence of the area of the curved surface **1110** from that of the two-dimensional projection **1800** is such that at the point on the perimeter **1151** of the curved surface **1110**, the area of the curved surface **1110** is 33.2% larger than at the corresponding point on the two-dimensional projection **1800**. The area of outer annulus **1150** characterized by lying between 90% and 100% of a distance from the centroid of the curved surface **1110** and the perimeter **1151** is proportionally 28.5 to 28.6% larger than the corresponding outer annulus on the two-dimensional projection **1800** than is an inner region characterized by lying between 0% and 10% of a distance from the centroid of the curved surface **1110** and the perimeter **1151** with respect to a corresponding inner region on the two-dimensional projection **1800**.

In a fourth example, an optical substrate **1100** such as a lens blank has a front surface characterized by a base curve of 6.00 diopter. The lens blank has a diameter of 80mm and a SAG number of 9.6mm. A virtual tangent line **1111** (or plane) drawn at a point on the edge of the curved surface **1110** forms an angle  $\alpha$  of 26.9° relative to the horizontal plane. The divergence of the area of the curved surface **1110** from that of the two-dimensional projection **1800** is such that at the point on the perimeter **1151** of the curved surface **1110**, the area of the curved surface **1110** is 12.2% larger than at the corresponding point on the two-dimensional projection **1800**. The area of outer annulus **1150** characterized by lying between 90% and 100% of a distance from the centroid of the curved surface **1110** and the perimeter **1151** is proportionally 10.8% larger than the corresponding outer annulus on the two-dimensional projection **1800** than is an inner region characterized by lying between 0% and 10% of a distance from the centroid of the curved surface **1110** and the perimeter **1151** with respect to a corresponding inner region on the two-dimensional projection **1800**.

In a fifth example, an optical substrate **1100** such as a lens blank has a front surface characterized by a base curve of 8.00 diopter. The lens blank has a diameter of 80mm and a SAG number of 13.4mm. A virtual tangent line **1111** (or plane) drawn at a point on the edge of the curved surface **1110** forms an angle  $\alpha$  of 37.1° relative to the horizontal plane. The divergence of the area of the curved surface **1110** from that of the two-dimensional projection **1800** is such that at the point on the perimeter **1151** of the curved surface **1110**, the area of the curved surface **1110** is 25.4% larger than at the corresponding point on the two-dimensional projection **1800**. The area of outer annulus **1150** characterized by lying between 90% and 100% of a distance from the centroid of the curved surface **1110** and the perimeter **1151** is proportionally 22.1 to 22.2% larger than the corresponding outer annulus on the two-dimensional projection **1800** than is an inner region characterized by lying between 0% and 10% of a distance from the centroid of the curved surface **1110** and the perimeter **1151** with respect to a corresponding inner region on the two-dimensional projection **1800**.

### **EXAMPLES**

Reference is now made to the following examples, which together with the above description, illustrate the invention in a non-limiting fashion.

#### **Materials**

##### **Lens Materials**

- polycarbonate, a thermoplastic polymer
- Trivex® (PPG), a urethane-based thermoset polymer
- CR-39® (PPG), a thermoset polymer made from allyl diglycol carbonate

##### **Photochromic Dyes (Powders, James Robinson Specialty Ingredients Ltd.):**

- Reversacol Amazon Green
- Reversacol Midnight Gray
- Reversacol Leather Brown
- Reversacol Corn Yellow
- Reversacol Ocean Blue

##### **Liquid Softening Agents**

- Emoltene™ 3GO (Perstorp) -- triethylenglycol-mono-2-ethyl-hexanoate
- Pevalen (Perstorp) -- pentaerythritol tetra valerate (PETV)
- Jayflex™ DIDP -- diisodecyl phthalate -- (Exxon Mobile)
- Jayflex™ L9TM -- tri-nonyl trimellitate (Exxon Mobile)
- Jayflex™ MB 10 -- iso-decyl benzoate (Exxon Mobile)

- DEHP - di-2-ethylhexyl phthalate (Arkema)
- DEHTP - di-2-ethylhexyl terephthalate (Arkema)
- Palatinol N - diisononyl phthalate (BASF)
- Palatinol 10-P – di-2-propylheptyl phthalate (BASF)
- Paraplex® A-8000 – low molecular weight polyester adipate (Hallstar)
- Paraplex® A-8200 – medium molecular weight polyester adipate (Hallstar)

### **Thermoplastic Resins**

- Pearlcoat™ DIPP 119 -- Aromatic polycaprolactone copolyester-based thermoplastic polyurethane (TPU) (Lubrizol)
- Pearlbond™ 360 -- Polyether based thermoplastic polyurethane (TPU) (Lubrizol)
- Pearlstick™ 47-60 linear thermoplastic polyurethane elastomers (Lubrizol)
- SETALUX® 2127 XX-60 -- Thermoplastic acrylic resin having good adhesion to plastics (Allnex)
- Polyvinyl butyral (or PVB), also for primers and overcoats
- Laropal A-81 -- Thermoplastic aldehyde resin (BASF).

### **Primers and Overcoats**

- **Acrylic polymer emulsions:**
  - Joncryl®1532 - waterborne acrylic emulsion offering excellent adhesion to a wide variety of substrates including plastics (BASF); Primer
  - Joncryl®1534 - waterborne acrylic emulsion offering excellent adhesion to a wide variety of substrates including plastics (BASF); Primer
  - Joncryl®2110 - waterborne acrylic emulsion, styrene acrylate copolymer (BASF); Primer
  - Joncryl®9530-A -- waterborne acrylic emulsion self-crosslinking polymer designed for use in topcoats and primers; Overcoat
  - Joncryl®617-A – waterborne acrylic polymer emulsion film forming overprint varnish formulations (BASF); Overcoat
  - SETALUX®17-7202 -- acetoacetate functional acrylic resin combined with a ketimine resin (SETALUX® 10-1440) for primer; Overcoat
  - SETALUX®17-1246 -- a fast-dry thermoplastic acrylic resin solution providing an excellent balance of hardness, adhesion and film toughness together with clarity and transparency; Overcoat
- **PU polymer emulsions and dispersions:**

- ALBERDINGK<sup>®</sup> APU 10600 self-crosslinking acrylic, PES/PC-polyurethane hybrid dispersion (Alberdingk Boley); Overcoat
- Bondthane<sup>™</sup> UD-620 -- self-crosslinking polyurethane is ideally suited for hard, clear or pigmented coatings for rigid plastics (BPI); Overcoat
- CrystalCoat<sup>®</sup> PR 670 -- water-based emulsion (SDC); Primer
- ALBERDINGK<sup>®</sup> U9800 -- solvent-free, aliphatic polyester polyurethane dispersion (Alberdingk Boley); Overcoat
- **Resin Solvent Based Solutions:**
  - Versamid<sup>®</sup>PUR 1010 -- Primer
  - Laroflex<sup>®</sup>HS-9000 -- Primer.

**Solvents: very low evaporation rate/ very low vapor pressure at 25°C**

- TPM (Tripropylene glycol methyl ether, CAS 25498-49-1)
- PPH (Ph-O-CH<sub>2</sub>-CHMe-OH, CAS 770-35-4)
- DBA (2-(2-Butoxyethoxy)ethyl acetate, CAS 124-17-4)
- TPnB (Tripropylene glycol n-butyl ether, 55934-93-5)
- DPnP (dipropylene glycol propyl ether, Pr-O-[CH<sub>2</sub>-CHMe-O]<sub>2</sub>-H, CAS 29911-27-1)
- acetone glycerol (ALDRICH, 2,2-dimethyl-1,3-dioxolane-4-methanol, CAS 100-79-8)
- butyl carbitol (CAS 112-34-5)
- EGBE (ethylene glycol monobutyl ether, CAS 111-76-2)

**Solvents: high evaporation rate/ high vapor pressure at 25°C**

- n-butyl acetate
- isobutyl acetate
- methyl isobutyl ketone
- isopropanol
- ethanol

**Solvents: very high evaporation rate/ high vapor pressure at 25°C**

- ethyl acetate
- methyl propyl ketone
- n-propyl acetate
- isopropyl acetate
- methyl ethyl ketone

**Equipment**

- Coating Equipment
  - Ink-Jet Printer: Dimatix Materials Printer DMP-2831 equipped with a 10 pL Dimatix Materials Cartridge (Fujifilm Dimatix™ Inc); Ricoh gen4I mh2620, driven by GIS PMB C8 and hib-rh-384 (Ink feeding System: MegnaJet LabJet)
  - Microvalve: electromagnetically actuated (Fritz Gyger AG); nozzle diameter -- 0.1mm, pressure 0.5-2.0 bar
  - Spin coater: MUTECH  $\mu$ Coater (Mutech Microsystems SAS)
  - UV LED Curing System: FJ100 Gen 2, 395nm, 12W/cm<sup>2</sup> (Phoseon Technology)
  - Thermal Curing System: Venticell ECO Forced air oven (MMM)
  - Surface Activation: Corona Treatment Device Electrical Surface Treatment HF SpotTEC Single (Tantec).
- Testing Equipment
  - Spectrophotometer: Cary 4000 UV-Vis. double-beam spectrophotometer, ISO/EN 8980-3:2013 (Agilent)
  - Light Transmittance and Haze Measuring Meter: TH-100, ASTM D1003/D1044 (Hangzhou CHN Spec Technology Co., Ltd.)
  - Thickness measurements: ThetaMetrisis layer thickness analyzer.

#### ***EXAMPLE 1: Corona Surface Treatment Procedure***

The head of the corona treatment device (Tantec) was set at 1cm from the surface of the ophthalmic lens and then was activated for 10 seconds. The process was performed twice before various coating materials were applied on the ophthalmic lens.

#### ***EXAMPLE 2: Procedure for Primer Application using Spin-Coating***

The ophthalmic lens was attached to the vacuum chuck of the spin coating apparatus. The spinning of the ophthalmic lens was performed at a spinning speed of 3000 rpm, an acceleration of 1000 rpm/sec, for 10 seconds.

#### ***EXAMPLE 3: Procedure for Application of post-Hardcoat Layers using Spin-Coating***

The ophthalmic lens was attached to the vacuum chuck of the spin coating apparatus. The spinning of the ophthalmic device was performed at a spinning speed of 1500 rpm, an acceleration of 500 rpm/sec, for 10 seconds.

#### ***EXAMPLE 4: Optimization of Ink-Jetting Parameters***

In various ink application steps, ink-jetting may optionally be employed, utilizing ink-jet ink formulations. A Ricoh print head was used, typically with pre-heating to 40°C. The drop characteristics were then optimized for each ink using a Jet Expert stroboscope (Image Expert) mounted on the printer (camera and light source synchronized with the jetting frequency). The

waveform was optimized for each ink-jet ink, jetted at a frequency of 0.5-3 kHz. The distance between the printhead and the substrate was 0.6-1.0 mm. The resolution was set at 300 dots per inch (dpi).

***EXAMPLE 5: Microvalving a Film-Forming Ink onto a Lens Substrate***

An optical construction having at least one of various functionalities (primer, photochromic inks, overcoats, hardcoats, post-hardcoat coatings, etc.) was prepared by microvalving a film-forming ink onto a lens substrate using an electromagnetically actuated microvalve (Fritz Gyger AG) having a nozzle diameter of 0.1mm. The microvalve was mounted on a controllable X-Y-Z stage, with a PLC synchronizing between the actuation of the microvalve and the positioning of the lens. Both frequency and relative velocity between the stage and the microvalve were maintained at fixed values. The microvalving was performed according to any one of various pre-determined digital patterns.

***EXAMPLE 6A: Drying***

Drying of the primer, overcoat, and photochromic ink was typically performed at 60°C for 30 minutes, unless otherwise indicated.

***EXAMPLE 6B: Thermal Curing***

Curing of the hardcoat (inner, when utilized, and outer) was typically performed at 120°C for 3 hours.

***EXAMPLE 6C: UV Curing***

UV curing was performed for 10 seconds using the UV LED Curing System: FJ100 Gen 2, 395nm, 12W/cm<sup>2</sup> (Phoseon Technology).

***EXAMPLE 7***

29 grams of DBA (2-(2-Butoxyethoxy)ethyl acetate) solvent were mixed with 66.6 grams of propylene glycol methyl ether solvent in a 200ml glass beaker equipped with a magnetic stirrer. After mixing the components for 5 minutes at room temperature, 0.2 grams of surfactant BYK®-333 were added to the solvent mixture while mixing. 2 grams of Reversacol Midnight Gray dye were then added, along with 2.2 grams of Pearlbond™ 360, while mixing. Mixing was continued for another 20 minutes at 60°C to produce the photochromic ink, which was subsequently filtered with a syringe filter (0.45 micrometer).

***EXAMPLE 8***

22 grams of DBA solvent were mixed with 72.3 grams of DPnP solvent in a 200ml glass beaker equipped with a magnetic stirrer. After mixing the components for 5 minutes, 0.15 grams of surfactant BYK®-346 and 1.45 grams of Emoltene™ 3GO were added to the solvent mixture while mixing. 2 grams of Reversacol Amazon Green dye, were then added, along with 2.1 grams of Mowital® B 30 HH resin, while mixing. Mixing was continued for another 20 minutes

at 60°C to produce the photochromic ink, which was subsequently filtered with a syringe filter (0.45 micrometer).

***EXAMPLE 9***

17 grams of TPM solvent were mixed with 74.5 grams of DPnP in a 200ml glass beaker equipped with a magnetic stirrer. After mixing the components for 5 minutes at room temperature, 0.25 grams of surfactant BYK®-346 and 1.85 grams of Emoltene™ 3GO were added to the solvent mixture while mixing. 2 grams of Reversacol Corn Yellow and 1.4 grams of Reversacol Ocean Blue dyes were then added, along with 3 grams of Mowital® B 16 H resin, while mixing. Mixing was continued for another 20 minutes at 60°C to produce the photochromic ink, which was subsequently filtered with a syringe filter (0.45 micrometer).

***EXAMPLE 10***

35.5 grams of TPM solvent were mixed with 55.4 grams of ethyl acetate solvent in a 200ml glass beaker equipped with a magnetic stirrer. After mixing the components for 5 minutes at room temperature, 2 grams of Pevalen were added to the solvent mixture while mixing. 1.6 grams of Reversacol Corn Yellow and 1.6 grams of Reversacol Ocean Blue dyes were then added, along with 3.8 grams of Pearlcoat™ DIPP 119 as a resin/binder, while mixing. Mixing was continued for another 20 minutes at 60°C to produce the photochromic ink, which was subsequently filtered with a syringe filter (0.45 micrometer).

***EXAMPLE 11***

13.7 grams of TPM solvent were mixed with 76.8 grams of isopropyl acetate in a 200ml glass beaker equipped with a magnetic stirrer. After mixing the components for 5 minutes at room temperature, 2.6 grams of Jayflex™ MB 10 were added to the solvent mixture while mixing. 0.9 grams of Reversacol Corn Yellow, 0.6 grams of Reversacol Ocean Blue, and 0.2 grams of Reversacol Leather Brown dyes were then added, along with 5.2 grams of Mowital® B 16 H resin, while mixing. Mixing was continued for another 20 minutes at 60°C to produce the photochromic ink, which was subsequently filtered with a syringe filter (0.45 micrometer).

***EXAMPLE 12***

11.8 grams of DBA solvent, 2 grams of PMA solvent, and 77 grams of n-propyl acetate solvent were mixed in a 200ml glass beaker equipped with a magnetic stirrer. After mixing for 5 minutes, 0.2 grams of surfactant BYK®-333 and 2.6 grams of Jayflex™ DIDP were added to the solvent mixture while mixing. 1.3 grams of Reversacol Corn Yellow and 1.3 grams of Reversacol Ocean Blue dyes were then added, along with 3.8 grams of Mowital® B 16 H resin, while mixing. Mixing was continued for another 20 minutes at 60°C to produce the photochromic ink, which was subsequently filtered with a syringe filter (0.45 micrometer).

***EXAMPLE 13***

41 grams of DBA solvent, 3 grams of isopropanol solvent, and 47 grams of methyl propyl ketone solvent were mixed in a 200ml glass beaker equipped with a magnetic stirrer. After mixing for 5 minutes, 0.2 grams of surfactant BYK®-333 and 2.3 grams of Palatinol N were added to the solvent mixture while mixing. 2.2 grams of Reversacol Corn Yellow and 1.4 grams of Reversacol Ocean Blue dyes were then added, along with 2.9 grams of Mowital® B 30 HH resin, while mixing. Mixing was continued for another 20 minutes at 60°C to produce the photochromic ink, which was subsequently filtered with a syringe filter (0.45 micrometer).

***EXAMPLE 14***

39 grams of DBA solvent, 12.8 grams of PMA solvent, and 40.5 grams of methyl propyl ketone solvent were mixed in a 200ml glass beaker equipped with a magnetic stirrer. After mixing for 5 minutes, 0.2 grams of surfactant BYK®-346 and 2.1 grams of Palatinol N were added to the solvent mixture while mixing. 2.2 grams of Reversacol Corn Yellow and 0.7 grams of Reversacol Ocean Blue dyes were then added, along with 2.5 grams of Mowital® B 30 HH resin, while mixing. Mixing was continued for another 20 minutes at 60°C to produce the photochromic ink, which was subsequently filtered with a syringe filter (0.45 micrometer).

***EXAMPLE 15***

35.5 grams of TPM solvent, 12.2 grams of n-butyl acetate solvent, and 43 grams of ethyl acetate solvent were mixed in a 200ml glass beaker equipped with a magnetic stirrer. After mixing the components for 5 minutes at room temperature, 0.2 grams of surfactant BYK®-333 and 1.5 grams of Jayflex™ DIDP were added to the solvent mixture while mixing. 1.6 grams of Reversacol Corn Yellow and 1.6 grams of Reversacol Ocean Blue dyes were then added, along with 3.9 grams of Mowital® B 16 H resin as a binder and 0.5 grams of Laropal A-81 resin as a solid softening agent, while mixing. Mixing was continued for another 20 minutes at 60°C to produce the photochromic ink, which was subsequently filtered with a syringe filter (0.45 micrometer).

***EXAMPLE 16***

34.4 grams of butyl carbitol solvent, 48 grams of isobutyl acetate solvent, and 10 grams of ethyl acetate solvent were mixed in a 200ml glass beaker equipped with a magnetic stirrer. After mixing the components for 5 minutes at room temperature, 0.1 grams of surfactant BYK®-358 and 1.5 grams of Jayflex™ MB 10 were added to the solvent mixture while mixing. 2 grams of Reversacol Amazon Green dye was then added, along with 2.9 grams of Mowital® B 16 H resin, while mixing. Mixing was continued for another 20 minutes at 60°C to produce the photochromic ink, which was subsequently filtered with a syringe filter (0.45 micrometer).

***EXAMPLE 17***

41 grams of acetone glycerol solvent, 6 grams of isopropanol solvent, and 43.3 grams of

methyl propyl ketone solvent were mixed in a 200ml glass beaker equipped with a magnetic stirrer. After mixing for 5 minutes, 0.2 grams of surfactant BYK®-346 and 2.5 grams of Palatinol N were added to the solvent mixture while mixing. 1.7 grams of Reversacol Corn Yellow and 1.9 grams of Reversacol Ocean Blue dyes were then added, along with 3.4 grams of Mowital® B 30 HH resin, while mixing. Mixing was continued for another 20 minutes at 60°C to produce the photochromic ink, which was subsequently filtered with a syringe filter (0.45 micrometer).

#### ***EXAMPLE 18***

13.7 grams of TPnB solvent were mixed with 28 grams of ethyl acetate solvent and 48.8 grams of DPnP solvent in a 200ml glass beaker equipped with a magnetic stirrer. After mixing the components for 5 minutes at room temperature, 2.6 grams of Jayflex™ MB 10 were added to the solvent mixture while mixing. 0.9 grams of Reversacol Corn Yellow, 0.6 grams of Reversacol Ocean Blue, and 0.2 grams of Reversacol Leather Brown dyes were then added, along with 5.2 grams of Pearlcoat™ DIPP 119 as a binder, while mixing. Mixing was continued for another 20 minutes at 60°C to produce the photochromic ink, which was subsequently filtered with a syringe filter (0.45 micrometer).

#### ***EXAMPLE 19***

11.3 grams of EB solvent, 10.2 grams of DBA solvent, and 68.2 grams of isopropyl acetate solvent were mixed in a 200ml glass beaker equipped with a magnetic stirrer. After mixing the components for 5 minutes at room temperature, 3.4 grams of Paraplex® A-8200 and 0.3 grams of surfactant BYK®-333 were added to the solvent mixture while mixing. 1.3 grams of Reversacol Corn Yellow, 1.3 grams of Reversacol Ocean Blue, and 0.5 grams of Reversacol Leather Brown dyes were then added, along with 5.5 grams of Mowital® B 16 H resin, while mixing. Mixing was continued for another 20 minutes at 60°C to produce the photochromic ink, which was subsequently filtered with a syringe filter (0.45 micrometer).

#### ***EXAMPLE 20***

4 grams of Mowital PVB 16H were mixed with 74 grams of TPM in a 200ml glass flask equipped with a magnetic stirrer. Then 1.5 grams of Jayflex™ DIDP, 19 grams of ethyl acetate solvent and 1.2 grams of Reversacol Leather Brown Dye was added while mixing. After mixing the components for 30 minutes, 0.3 grams of surfactant BYK®307 were added to the mixture and the mixing was continued for another 10 minutes at 30°C.

#### ***EXAMPLE 21***

3.7 grams of Mowital PVB 30HH were mixed with 77 grams of TPM in a 200ml glass flask equipped with a magnetic stirrer. Then 1.3 grams of Jayflex™ MB 10, 16.7 grams of ethyl acetate solvent and 1.05 grams of Reversacol Amazon Green Dye were added while mixing.

After mixing the components for 30 minutes, 0.25 grams of surfactant BYK®307 were added to the mixture and the mixing was continued for another 10 minutes at 30°C.

***EXAMPLE 22***

65 grams of Joncryl®1532 were mixed with 20 grams of water in a 200ml glass beaker equipped with a magnetic stirrer. Then 9.5 grams of EB solvent, 4.8 grams of DPM solvent and 0.2 grams of BYK®024 were added while mixing. After mixing the components for 5 minutes, 0.5 grams of surfactant BYK®-346 were added to the mixture and the mixing was continued for another 10 minutes at 30°C, to produce a primer formulation.

***EXAMPLE 23***

70 grams of Joncryl®1534 were mixed with 15 grams of water in a 200ml glass beaker equipped with a magnetic stirrer. Then 9.5 grams of EB solvent, 4.8 grams of DPM solvent and 0.2grams of BYK®024 were added while mixing. After mixing the components for 5 minutes, 0.5 grams of surfactant EFKA®3200 were added to the mixture and the mixing was continued for another 10 minutes at 30°C, to produce a primer formulation.

***EXAMPLE 24***

75 grams of Joncryl®2110 were mixed with 10 grams of water in a 200ml glass beaker equipped with a magnetic stirrer. Then 10 grams of EB solvent, 4.5 grams of DPM solvent and 0.25 grams of BYK®044 were added while mixing. After mixing the components for 5 minutes, 0.25 grams of surfactant BYK®346 were added to the mixture and the mixing was continued for another 10 minutes at 30°C, to produce a primer formulation.

***EXAMPLE 25***

2.0 grams of Mowital PVB 16H were mixed with 97.7 grams of ethyl acetate in a 200ml glass flask equipped with a magnetic stirrer. After mixing the components for 30 minutes, 0.3 grams of surfactant BYK®-307 were added to the mixture and the mixing was continued for another 10 minutes at 30°C, to produce a primer formulation.

***EXAMPLE 26***

1.77 grams of Mowital PVB 30H were mixed with 98.2 grams of ethyl acetate in a 200ml glass flask equipped with a magnetic stirrer. After mixing the components for 30 minutes, 0.3 grams of surfactant BYK®-307 were added to the mixture and the mixing was continued for another 10 minutes at 30°C, to produce a primer formulation.

***EXAMPLE 27***

2.0 grams of Pearlcoat™ DIPP 119 were mixed with 98 grams of ethyl acetate in a 200ml glass flask equipped with a magnetic stirrer at 40°C for 1 hour. After mixing the components for

60 minutes, 0.3 grams of surfactant BYK<sup>®</sup>-307 were added to the mixture and the mixing was continued for another 20 minutes to produce a primer formulation.

***EXAMPLE 28***

2.0 grams of Pearlstick<sup>™</sup> 47-60 were mixed with 98 grams of ethyl acetate in a 200ml glass flask equipped with a magnetic stirrer at 40°C for 1 hour. After mixing the components for 60 minutes, 0.3 grams of surfactant BYK<sup>®</sup>-307 were added to the mixture and the mixing was continued for another 20 minutes to produce a primer formulation.

***EXAMPLE 29***

80 grams of U9800 were mixed with 19.5 grams of water, and 0.5 gram of BYK 346 in a 200ml glass flask equipped with a magnetic stirrer for 1 hour to produce an overcoat formulation.

***EXAMPLE 30***

The corona surface treatment procedure was performed on a Trivex<sup>®</sup> (PPG) lens, according to Example 1.

***EXAMPLE 31***

The corona surface treatment procedure was performed on a polycarbonate lens according to Example 1.

***EXAMPLE 32***

The corona surface treatment procedure of Example 1 was performed on a polycarbonate lens that was pre-coated with a hardcoat.

***EXAMPLE 33***

The corona surface treatment procedure of Example 1 was performed on a Trivex<sup>®</sup> (PPG) lens that was pre-coated with a hardcoat.

***EXAMPLE 34***

The corona surface treatment procedure of Example 1 was performed on a CR-39<sup>®</sup> (PPG) lens that was pre-coated with a hardcoat.

***EXAMPLE 35***

Onto a polycarbonate lens was applied Versamid<sup>®</sup>PUR 1010 as a primer. Microvalving was effected according to Example 5, and a calculated (average) wet thickness of 6.8µm was obtained. The wet layer was then subjected to thermal drying and curing in a Venticell ECO forced air oven at 60°C for 10 minutes and then at 100°C for 10 minutes, to produce the primer layer.

***EXAMPLE 36***

Onto a polycarbonate lens was applied Laroflex<sup>®</sup>HS-9000 as a primer. Microvalving was

effected according to Example 5, and a calculated wet thickness of 5.9 $\mu$ m was obtained. The wet layer was then subjected to thermal drying and curing in a Venticell ECO forced air oven at 60°C for 10 minutes and then at 100°C for 10 minutes, to produce a primer layer having a thickness of about 1.5 $\mu$ m.

#### EXAMPLE 37

Onto a polycarbonate lens was applied the Joncryl<sup>®</sup>1534 formulation of Example 23 as a primer. Spin coating was effected according to Example 2, and a calculated wet thickness of 1.9 $\mu$ m was obtained. The wet layer was then subjected to thermal drying and curing in a Venticell ECO forced air oven at 60°C for 10 minutes and then at 100°C for 10 minutes.

#### EXAMPLE 38

Onto the polycarbonate lens that had been corona-treated according to Example 32 was applied the Joncryl<sup>®</sup>1534 formulation of Example 23 as a primer. Spin coating was effected according to Example 2. The wet layer was then subjected to thermal drying and curing in a Venticell ECO forced air oven at 60°C for 10 minutes and then at 100°C for 10 minutes.

#### EXAMPLES 39-53: Microvalving a Photochromic Ink onto the Surface of the Lens

Photochromic dye formulations of Examples 7-21, which contain photochromic dye, a polymeric binder, and typically -- a non-volatile liquid softening agent --were microvalved onto various lens substrates according to Example 5, at a pressure maintained below 1 bar. The microvalving experiments are delineated in the table provided below:

| Example No. | Photochromic Dye Formulation | Lens Material       | precoated / unprecoated |
|-------------|------------------------------|---------------------|-------------------------|
| Example 39  | Example 7                    | CR-39 <sup>®</sup>  | precoated               |
| Example 40  | Example 8                    | CR-39 <sup>®</sup>  | precoated               |
| Example 41  | Example 9                    | CR-39 <sup>®</sup>  | precoated               |
| Example 42  | Example 10                   | CR-39 <sup>®</sup>  | precoated               |
| Example 43  | Example 11                   | CR-39 <sup>®</sup>  | precoated               |
| Example 44  | Example 12                   | CR-39 <sup>®</sup>  | unprecoated             |
| Example 45  | Example 13                   | Trivex <sup>®</sup> | precoated               |
| Example 46  | Example 14                   | Trivex <sup>®</sup> | precoated               |
| Example 47  | Example 15                   | Trivex <sup>®</sup> | precoated               |
| Example 48  | Example 16                   | polycarbonate       | precoated               |
| Example 49  | Example 17                   | polycarbonate       | precoated               |
| Example 50  | Example 18                   | polycarbonate       | precoated               |
| Example 51  | Example 19                   | polycarbonate       | precoated               |
| Example 52  | Example 20                   | polycarbonate       | unprecoated             |
| Example 53  | Example 21                   | polycarbonate       | unprecoated             |

#### EXAMPLE 54

Onto the coated CR-39<sup>®</sup> lens produced in Example 34 was microvalved the overcoat formulation of Example 29. The wet layer, having a calculated average wet thickness of 11 $\mu$ m,

was then subjected to thermal drying in a Venticell ECO forced air oven at 60°C for 30 minutes. The dry (average calculated) thickness was about 3.1 μm.

#### ***EXAMPLES 55-59: Hardcoat Varnish Formulation***

##### ***Example 55: Hardcoat Varnish***

15.0 grams of 3-glycidoxypentyltrimethoxysilane, 33.6 grams of tetraethyl orthosilicate, 22.5 grams of itaconic acid and 24.8 grams of ethyl acetate were combined while being stirred for 10 minutes until a homogeneous mixture was achieved. 24.8 grams of water were added dropwise on top of the premixed silane solution by a peristaltic pump to make the resulting mixture. The mixture was then stirred for 12 hours to produce a coating composition.

##### ***Example 56: HC Varnish + Catalyst***

0.2 grams of benzyldimethylamine was added dropwise to 99.8 grams of the mixture from Example 44 and mixed for 10 hours.

##### ***Example 57: HC Varnish + Nanoparticles***

15.5 grams of 3-glycidoxypentyltrimethoxysilane, 25.5 grams of tetraethyl orthosilicate, 2.3 grams of itaconic acid and 23.2 grams of ethyl acetate were combined while being stirred for 20 minutes until a homogeneous mixture was achieved. 19.1 grams of water were added to 16.3 grams of Ludox HS-30 (Grace) nanosilica colloidal dispersion and mixed for 15 minutes and then it was added dropwise on top of the premixed silane solution by a peristaltic pump to make the resulting mixture. The mixture was then stirred for 24 hours to produce a coating composition.

##### ***Example 58: HC Varnish + Silane Additive***

12.0 gram of methyltrimethoxysilane (Gelest), 8.0 grams of 3-glycidoxypentyltrimethoxysilane (Gelest), 29.1 grams of tetraethyl orthosilicate (Merck), 22.5 grams of succinic anhydride (Merck) and 24.8 grams of isopropyl acetate (Dow) were combined while being stirred for 10 minutes until a homogeneous mixture was achieved. 24.8 grams of water were added dropwise on top of the premixed silane solution by a peristaltic pump to make the resulting mixture. The mixture was then stirred for 7 hours to produce a coating composition.

##### ***Example 59: HC Varnish + Catalyst***

1.5 gram of 10% w/w of potassium hydroxide water solution was added dropwise to 98.5 grams of the mixture from Example 58 and mixed for 15 hours.

#### ***EXAMPLE 60: Measuring Haze & % Transmittance***

After calibrating the T-100 instrument, the Target lens was measured (uncoated reference lens). In Sample mode, the coated lens was then tested. The instrument then displayed the following results of the coated and uncoated lenses: % Transmittance, Δ % Transmittance, Haze,

and  $\Delta$  Haze. Lower delta values between the coated and uncoated lens indicate good optical clarity/transparency.

***EXAMPLE 61: Measuring Photochromic properties***

Spectrophotometric studies were conducted using a Cary 4000 UV-Vis. double-beam spectrophotometer. The light source was a UV-LED lamp (395 nm). Activation and fading properties & kinetics were characterized. In the spectrophotometric studies, the coated samples were characterized against an uncoated reference slide or lens. Spectrum data were normally collected in the range 350-700nm at a resolution of 1nm. Kinetics measurements of activation and fading rates were performed at the wavelength of maximal absorbance for each photochromic dye, with a typical resolution of 0.2 seconds. The measurements were initiated while the UV-LED lamp is off. After 3-5 seconds, the UV-LED lamp was turned on for 120-180 seconds to attain maximal absorbance. The lamp was then turned off, and monitoring of the fading was conducted.

As used herein in the specification and in the claims section that follows, the term “percent”, or “%”, refers to percent by weight, unless specifically indicated otherwise.

As used herein in the specification and in the claims section that follows, the terms “anti-glare”, “anti-reflectance”; “anti-fog”; “hardcoat”; “ultraviolet absorber”; “photochromic”, “tinting” “blue-light absorber”, and the like, unless otherwise specified, are meant as used in the art of optical substrate coatings.

As used herein in the specification and in the claims section that follows, the term “anti-scratch”, with respect to a material such as a formulation or a coating, refers to a material whose dried and cured coating exhibits a haze value of less than 6%, using the following taber abrasion properties, according to ASTM D1004-08: CS 10 F wheel, 500g Load, 500 cycles.

Alternatively, the term “anti-scratch”, with respect to a material such as a formulation or a coating, refers to a material whose Bayer number is at least 5 or at least 6 when using ASTM F735-21.

The term “ratio”, as used herein in the specification and in the claims section that follows, refers to a weight ratio, unless specifically indicated otherwise.

As used herein in the specification and in the claims section that follows, the term “non-volatile component”, with respect to a formulation or formulation on a lens/optical substrate, relates to the residue left after driving off some or all of the solvents and carrier liquids from the lens/optical surface after subjecting the lens/optical substrate, coated with the formulation, to oven-drying at 120°C for 3 hours. The residue includes the solid particles within the formulation, along with dissolved solids that remain after the solvent has been removed.

As used herein in the specification and in the claims section that follows, the term “drying/curing” (e.g., of a formulation or layer) refers to drying or otherwise curing of the formulation or layer. It will be appreciated that for many types of formulations, thermal drying is a mechanism for effecting full curing.

As used herein in the specification and in the claims section that follows, the term “complete drying and curing” refers to complete removal of the liquid solvent/carrier along with 100% curing of the layer or coating.

As used herein in the specification and in the claims section that follows, the terms “fully curing” and “fully cured” (e.g., of a formulation or layer) refers to at least 85% curing of the polymeric material, as determined by a König hardness test according to ASTM D4366 Standard Test Methods for Hardness of Organic Coatings by Pendulum Damping Tests. Thus, for a reference polymer sheet that is 100% completely cured, having a König hardness of 80, the identical material that is “fully-cured” or has undergone “full curing” would have a König hardness within a range of 68 ( $0.85 \cdot 80$ ) to 80. Thus, the “fully cured” polymeric material has a minimum hardness coefficient ( $C_H$ ) of at least 0.85.

The “thickness” of a layer or a plurality of layers at a particular location is measured in the direction that is normal (**N**) to the lens substrate at that location.

Various types of thin-film thickness measurements are known to those of skill in the art. For example, single-spot thickness measurements may be performed by spectral reflectance or by spectroscopic ellipsometry.

In addition, mapping of thin-film surfaces and calculation of average thicknesses of such films may be performed using these techniques.

The “average thickness” of a wet layer may be determined as follows: when a volume of material  $vol$  covers a surface area of a surface having an area  $SA$  with a wet layer - the thickness of the wet layer is assumed to be  $vol/SA$ . If the weight of the materials is known,  $vol$  may be calculated by dividing by the material’s specific gravity. Typically, the specific gravity of the various coating materials may safely be approximated as 1.00.

The “average thickness” of a dried film may be calculated as follows: when a volume of material  $vol$  that is  $x\%$  liquid, by weight, wets or covers a surface area  $SA$  of a surface, and all the liquid is evaporated away to convert the wet layer into a dry film, the thickness of the dry film is calculated as:

$$vol/\rho_{\text{wet layer}} (100 - x) / (SA \cdot \rho_{\text{dry layer}})$$

where  $\rho_{\text{wet layer}}$  is the specific gravity of the wet layer and  $\rho_{\text{dry layer}}$  is the specific gravity of the dry layer. This calculation requires a knowledge of various properties of the wet coating material of

the film, e.g., the specific gravity. As mentioned above, typically, the specific gravities generally may be assumed to be 1.

Similarly, an average diameter of drops such as jetted or microvalved drops (**Ddrop**) may be calculated by weighing a large number of the jetted drops, converting the total weight into volume using the specific gravity, dividing by the number of drops, and utilizing the equation relating spherical drop diameter to sphere volume:  $D = (6 \cdot V / \pi)^{1/3}$ .

It will be appreciated by those of skill in the art that the various layers disposed on the optical or ophthalmic surface (e.g., the lens surface) of the present invention are generally of a substantially even thickness, hence, the “average thickness” may be determined by evaluating one or more spot thicknesses on the film or layer.

As used herein in the specification and in the claims section that follows, the term “characteristic”, with respect to an ink dot dimension such as height, length or diameter, refers to the maximal value of that dot dimension. By way of example, for a square dot, 30 micrometers on a side, the characteristic diameter would be the diagonal, i.e.,  $30\sqrt{2} = 42.4$  micrometers. For a dot having some peaks on the top surface, distal to the optical substrate, the dot height would be the maximum height measured normal to the top surface of the substrate. For a plurality of dots, the characteristic dimension is the average of the characteristic dimension of the individual dots within the plurality.

As used herein in the specification and in the claims section that follows, the term “average”, with respect to a dimension of a plurality of dots such as the height, length or diameter thereof, refers to the arithmetic mean of that dimension, and is calculated using the characteristic dimension for each dot in the plurality.

As used herein in the specification and in the claims section that follows, the term “transparent”, typically with respect to a material, e.g., a material used in a coating, or as a substrate, may be determined according to ASTM D1003. Utilizing ASTM D1003, a material having a haze measurement of less than 2% and a total transmittance ( $T_t$ ) of at least 85% is considered “transparent”. More typically, the haze is at most 1.5% or at most 1.0%. More typically,  $T_t$  is at least 90% or at least 95%. Yet more typically, the haze is at most 1.0% and  $T_t$  is at least 95%.

As used herein in the specification and in the claims section that follows, the term “liquid medium” and the like refers to a medium that is liquid at its temperature of use. For example, the liquid medium in an ink-jet ink jetted at 38°C is a liquid at 38°C. A “liquid medium” is typically liquid at 25°C.

The term “ophthalmic formulation”, is meant to be understood as used in the art of ophthalmic substrate coatings.

The term “non-volatile”, e.g., with regard to a liquid softening agent, is meant to be understood as generally used in solvent-based formulations.

Similarly, the term “non-volatile content”, typically with respect to a formulation such as an ink formulation, is meant to be understood as generally used in solvent-based formulations. It is specifically meant to include high-boiling point liquids such as glycerol (290°C).

As used herein, the term “film-forming”, typically with respect to a resin, polymer, or formulation, is meant to be understood as generally used in the art of ophthalmic substrate coatings. Typically, the dry film of the film-forming materials has an average or characteristic thickness ranging from 0.2 to 5 micrometers.

As used herein in the specification and in the claims section that follows, the term “softening agent” and the like is used essentially as understood in the art.

As used herein in the specification and in the claims section that follows, the term “liquid” refers to the state of the material at 25°C.

As used herein in the specification and in the claims section that follows, the terms “**LLevap**”, “**Levap**”, “**Mevap**”, “**Hevap**”, and “**HHevap**”, refer to volatile liquids falling within respective characteristic ranges of relative evaporation rates with respect to n-butyl acetate at 25°C and atmospheric pressure, according to ASTM D3539. More particularly, the volatile liquids are divided into 5 categories, as follows:

**LLevap** < 0.1 (e.g.: TPM, DPM, EB, NMP, DMSO, ethylene glycol monobutyl ether, DPM acetate)

$0.1 \leq \text{Levap} < 0.5$  (e.g.: EEP, EP, PP, PMA, n-butyl propionate, n-butanol, amyl acetate, water)

$0.5 \leq \text{Mevap} < 0.85$  (e.g.: PM, isobutanol)

$0.85 \leq \text{Hevap} < 1.8$  (e.g.: xylene, n-butyl acetate, isobutyl acetate, methyl isobutyl ketone, isopropanol, ethanol)

$1.8 \leq \text{HHevap}$  (e.g.: toluene, methanol, n-propyl acetate, isopropyl acetate, ethyl acetate, methyl propyl ketone, methyl ethyl ketone).

The designated standard material, n-butyl acetate, is assigned a vaporization or evaporation rate of 1.0. Thus, the term “relative evaporation rate” and the like is used with reference to n-butyl acetate.

In the context of the present application and claims, the phrase “at least one of A and B” is equivalent to an inclusive “or”, and includes any one of “only A”, “only B”, or “A and B”. Similarly, the phrase “at least one of A, B, and C” is equivalent to an inclusive “or”, and includes any one of “only A”, “only B”, “only C”, “A and B”, “A and C”, “B and C”, or “A and B and C”.

As used herein in the specification and in the claims section that follows, the terms “top”, “bottom”, “above”, “below”, “upper”, “lower”, “height” and “side” and the like are utilized for

convenience of description or for relative orientation, and are not necessarily intended to indicate an absolute orientation in space.

Additional Embodiments:

Various formulations, methods, optical constructions, and systems are disclosed herein. Additional Embodiments are provided hereinbelow.

INK FORMULATION EMBODIMENTS

1. An ink formulation comprising:
  - (a) a resin;
  - (b) a photochromic dye;
  - (c) a softening agent for softening the resin; and
  - (d) a solvent system including a very low vapor-pressure solvent (**LLevap**) and at least one of a low vapor-pressure solvent (**Levap**), a medium vapor-pressure solvent (**Mevap**), a high vapor-pressure solvent (**Hevap**) and a very high vapor-pressure solvent (**HHevap**);wherein the softening agent is optionally a non-volatile liquid softening agent; and wherein the resin and the photochromic dye are dissolved within the solvent system.
2. The formulation of Embodiment 1, wherein the solvent system, and the softening agent form a single liquid phase.
3. The formulation of Embodiment 1 or 2, wherein the formulation is a film-forming formulation.
4. The formulation of any previous Embodiment, wherein the formulation is devoid of pigment or photochromic pigment.
5. The formulation of any previous Embodiment, wherein the formulation is suitable for forming an ophthalmic film on an ophthalmic substrate.
6. The formulation of any previous Embodiment, wherein the resin is an ophthalmic, film-forming resin.
7. The formulation of any previous Embodiment, wherein the non-volatile content of the formulation is within a range of 2.5 to 15%.
8. The formulation of any previous Embodiment, wherein a first weight ratio of the resin to the photochromic dye is at least 0.5:1.
9. The formulation of Embodiment 8, wherein the first weight ratio is at least 1.25:1.
10. The formulation of Embodiment 8, wherein the first weight ratio is at least 1.75:1.
11. The formulation of Embodiment 8, wherein the first weight ratio is at least 2.25:1.
12. The formulation of Embodiment 8, wherein the first weight ratio is at least 2.6:1.
13. The formulation of Embodiment 8, wherein the first weight ratio is at least 3:1.

14. The formulation of any of Embodiments 8 to 13, wherein the first weight ratio is at most 7:1.
15. The formulation of Embodiment 14, wherein the first weight ratio is at most 5.5:1.
16. The formulation of Embodiment 14, wherein the first weight ratio is at most 4.5:1.
17. The formulation of Embodiment 14, wherein the first weight ratio is at most 3.5:1.
18. The formulation of any previous Embodiment, wherein the softening agent is the non-volatile liquid softening agent.
19. The formulation of Embodiment 18, wherein a second weight ratio of the non-volatile liquid softening agent to the photochromic dye is at least 0.2:1.
20. The formulation of Embodiment 19, wherein the second weight ratio is at least 0.25:1.
21. The formulation of Embodiment 19, wherein the second weight ratio is at least 0.3:1.
22. The formulation of Embodiment 19, wherein the second weight ratio is at least 0.4:1.
23. The formulation of Embodiment 19, wherein the second weight ratio is at least 0.6:1 or at least 0.8:1.
24. The formulation of any of Embodiments 19 to 23, wherein the second weight ratio is at most 2:1.
25. The formulation of Embodiment 24, wherein the second weight ratio is at most 1.4:1.
26. The formulation of Embodiment 24, wherein the second weight ratio is at most 1.1:1.
27. The formulation of Embodiment 24, wherein the second weight ratio is at most 0.85:1.
28. The formulation of any of Embodiments 19 to 23, wherein the second weight ratio is at most 0.75.
29. The formulation of any of Embodiments 19 to 22, wherein the second weight ratio is at most 0.6.
30. The formulation of any previous Embodiment, wherein a minimum film-forming temperature (MFFT) of the resin (polymer) is at most 90°C.
31. The formulation of Embodiment 30, wherein the MFFT is at most 60°C.
32. The formulation of Embodiment 30, wherein the MFFT is at most 50°C.
33. The formulation of Embodiment 30, wherein the MFFT is at most 40°C.
34. The formulation of Embodiment 30, wherein the MFFT is at most 35°C.
35. The formulation of Embodiment 30, wherein the MFFT is at most 30°C.
36. The formulation of Embodiment 30, wherein the MFFT is at most 25°C.
37. The formulation of Embodiment 30, wherein the MFFT is at most 20°C.
38. The formulation of Embodiment 30, wherein the MFFT is at most 15°C.
39. The formulation of Embodiment 30 to 38, wherein the MFFT is at least -50°C.
40. The formulation of Embodiment 39, wherein the MFFT is at least -35°C.
41. The formulation of Embodiment 39, wherein the MFFT is at least -20°C.

42. The formulation of Embodiment 39, wherein the MFFT is at least -10°C.
43. The formulation of any previous Embodiment, wherein a 25°C static viscosity of the formulation is at most 65cP.
44. The formulation of Embodiment 43, wherein the viscosity is at most 50cP.
45. The formulation of Embodiment 43, wherein the viscosity is at most 35cP.
46. The formulation of Embodiment 43, wherein the viscosity is at most 25cP.
47. The formulation of Embodiment 43, wherein the viscosity is at most 20cP.
48. The formulation of Embodiment 43, wherein the viscosity is at most 15cP.
49. The formulation of Embodiment 43, wherein the viscosity is at most 12cP.
50. The formulation of any one of Embodiments 43 to 49, wherein the viscosity of the liquid film-forming formulation is at least 1.5cP.
51. The formulation of Embodiment 50, wherein the viscosity is at least 2.5cP.
52. The formulation of Embodiment 50, wherein the viscosity is at least 4cP.
53. The formulation of Embodiment 50, wherein the viscosity is at least 6cP.
54. The ink formulation of any previous Embodiment, wherein the non-volatile content of the formulation is at least 5%.
55. The formulation of Embodiment 54, wherein the non-volatile content is at least 7%.
56. The formulation of Embodiment 54, wherein the non-volatile content is at least 9%.
57. The formulation of Embodiment 54, wherein the non-volatile content is at least 10%.
58. The formulation of Embodiment 54, wherein the non-volatile content is at least 11%.
59. The formulation of Embodiment 54, wherein the non-volatile content is at least 12%.
60. The ink formulation of any previous Embodiment, wherein the non-volatile content of the formulation is at most 20%.
61. The formulation of Embodiment 60, wherein the non-volatile content is at most 18%.
62. The formulation of Embodiment 60, wherein the non-volatile content is at most 16.5%.
63. The formulation of Embodiment 60, wherein the non-volatile content is at most 15.5%.
64. The formulation of Embodiment 60, wherein the non-volatile content is at most 15%.
65. The formulation of Embodiment 60, wherein the non-volatile content is at most 14.5%.
66. The formulation of Embodiment 60, wherein the non-volatile content is at most 14%.
67. The formulation of any one of the preceding Embodiments, wherein a weight ratio of liquid to polymer **R<sub>P-L</sub>** within the ink formulation is at most 0.20.
68. The formulation of Embodiment 67, wherein **R<sub>P-L</sub>** is at most 0.18.
69. The formulation of Embodiment 67, wherein **R<sub>P-L</sub>** is at most 0.16.
70. The formulation of Embodiment 67, wherein **R<sub>P-L</sub>** is at most 0.14.
71. The formulation of any one of Embodiments 67 to 70, wherein **R<sub>P-L</sub>** is at least 0.06.

72. The formulation of Embodiment 71, wherein  $R_{P-L}$  is at least 0.08.
73. The formulation of Embodiment 71, wherein  $R_{P-L}$  is at least 0.09.
74. The formulation of Embodiment 71, wherein  $R_{L-P}$  is at least 0.095.
75. The formulation of Embodiment 71, wherein  $R_{P-L}$  is at least 0.1.
76. The formulation of Embodiment 67, wherein  $R_{P-L}$  is within a range of 0.075 to 0.15.
77. The formulation of Embodiment 67, wherein  $R_{P-L}$  is within a range of 0.085 to 0.135.
78. The formulation of Embodiment 67, wherein  $R_{P-L}$  is within a range of 0.09 to 0.13.
79. The formulation of any of preceding Embodiment, wherein a 25°C surface tension  $\sigma$  of the ink formulation is at most 35 dyne/cm.
80. The formulation of Embodiment 79, wherein  $\sigma$  is at most 32 dyne/cm.
81. The formulation of Embodiment 79, wherein  $\sigma$  is at most 30 dyne/cm.
82. The formulation of Embodiment 79, wherein  $\sigma$  is at most 29 dyne/cm.
83. The formulation of any of Embodiments 79 to 82, wherein  $\sigma$  of the ink formulation is at least 24 dyne/cm.
84. The formulation of Embodiment 83, wherein  $\sigma$  is at least 25 dyne/cm.
85. The formulation of Embodiment 83, wherein  $\sigma$  is at least 26 dyne/cm.
86. The formulation of any preceding Embodiment, wherein at least 85 weight% of the total polymer content within the ink formulation is a film-forming polymer.
87. The formulation of Embodiment 86, wherein at least 90 weight% of the total polymer content within the ink formulation is a film-forming polymer.
88. The formulation of any preceding Embodiment, wherein, on an n-butyl acetate normalized 25°C evaporation rate scale, at least 50% of the total solvent within the formulation is at most a high vapor-pressure solvent (**Hevap**), on a weight basis.
89. The formulation of Embodiment 88, at least 60% of the total solvent being at most **Hevap**.
90. The formulation of Embodiment 88, at least 70% of the total solvent being at most **Hevap**.
91. The formulation of Embodiment 88, at least 80% of the total solvent being at most **Hevap**.
92. The formulation of Embodiment 88, at least 90% of the total solvent being at most **Hevap**.
93. The formulation of Embodiment 88, at least 95% of the total solvent being at most **Hevap**.
94. The formulation of any preceding Embodiment, wherein, on an n-butyl acetate normalized 25°C evaporation rate scale, at least 70% of the total solvent within the formulation is at most a medium vapor-pressure solvent (**Mevap**), on a weight basis.
95. The formulation of Embodiment 94, at least 75% of the total solvent being at most **Mevap**.
96. The formulation of Embodiment 94, at least 80% of the total solvent being at most **Mevap**.
97. The formulation of Embodiment 94, at least 85% of the total solvent being at most **Mevap**.

98. The formulation of Embodiment 94, at least 85% of the total solvent being at most **Mevap**.
99. The formulation of any preceding Embodiment, wherein, on an n-butyl acetate normalized 25°C evaporation rate scale, at least 25% of the total solvent within the formulation is at most a low vapor-pressure solvent (**Levap**), on a weight basis.
100. The formulation of Embodiment 94, at least 30% of the total solvent being at most **Levap**.
101. The formulation of Embodiment 94, at least 40% of the total solvent being at most **Levap**.
102. The formulation of Embodiment 94, at least 50% of the total solvent being at most **Levap**.
103. The formulation of Embodiment 94, at least 60% of the total solvent being at most **Levap**.
104. The formulation of Embodiment 94, at least 70% of the total solvent being at most **Levap**.
105. The formulation of Embodiment 94, at least 80% of the total solvent being at most **Levap**.
106. The formulation of any preceding Embodiment, wherein, on an n-butyl acetate normalized 25°C evaporation rate scale ( $S_{nba}$ ), at least 30% of the total solvent (**Ts**) within the formulation has a relative evaporation rate (**Rev**) of at most 0.35, on a weight basis.
107. The formulation of Embodiment 106, wherein, for at least 40% of **Ts**, **Rev** is at most 0.35.
108. The formulation of Embodiment 106, wherein, for at least 50% of **Ts**, **Rev** is at most 0.35.
109. The formulation of Embodiment 106, wherein, for at least 60% of **Ts**, **Rev** is at most 0.35.
110. The formulation of Embodiment 106, wherein, for at least 70% of **Ts**, **Rev** is at most 0.35.
111. The formulation of Embodiment 106, wherein, for at least 75% of **Ts**, **Rev** is at most 0.35.
112. The formulation of Embodiment 106, wherein, for at least 80% of **Ts**, **Rev** is at most 0.4.
113. The formulation of Embodiment 106, wherein, for at least 90% of **Ts**, **Rev** is at most 0.4.
114. The formulation of Embodiment 106, wherein, for at least 50% of **Ts**, **Rev** is at most 0.6.
115. The formulation of Embodiment 106, wherein, for at least 60% of **Ts**, **Rev** is at most 0.6.
116. The formulation of Embodiment 106, wherein, for at least 70% of **Ts**, **Rev** is at most 0.6.
117. The formulation of Embodiment 106, wherein, for at least 75% of **Ts**, **Rev** is at most 0.6.
118. The formulation of Embodiment 106, wherein, for at least 80% of **Ts**, **Rev** is at most 0.6.
119. The formulation of Embodiment 106, wherein, for at least 90% of **Ts**, **Rev** is at most 0.6.
120. The formulation of any preceding Embodiment, wherein, on an n-butyl acetate normalized 25°C evaporation rate scale, at least 20% of the total solvent (**Ts**) within the formulation is at most a very low vapor-pressure solvent (**LLevap**), on a weight basis.
121. The formulation of Embodiment 120, at least 30% of **Ts** being at most **LLevap**.
122. The formulation of Embodiment 120, at least 35% of **Ts** being at most **LLevap**.
123. The formulation of Embodiment 120, at least 40% of **Ts** being at most **LLevap**.
124. The formulation of Embodiment 120, at least 40% of **Ts** being at most **LLevap**.
125. The formulation of Embodiment 120, at least 50% of **Ts** being at most **LLevap**.
126. The formulation of Embodiment 120, at least 55% of **Ts** being at most **LLevap**.

127. The formulation of Embodiment 120, at least 60% of **Ts** being at most **LLevap**.
128. The formulation of Embodiment 120, at least 65% of **Ts** being at most **LLevap**.
129. The formulation of Embodiment 120, at least 70% of **Ts** being at most **LLevap**.
130. The formulation of Embodiment 120, at least 75% of **Ts** being at most **LLevap**.
131. The formulation of any previous Embodiment, wherein the relative evaporation rate of **LLevap** (**R<sub>LL</sub>**) is at most 0.05.
132. The formulation of Embodiment 131, wherein **R<sub>LL</sub>** is at most 0.025.
133. The formulation of Embodiment 131, wherein **R<sub>LL</sub>** is at most 0.015.
134. The formulation of Embodiment 131, wherein **R<sub>LL</sub>** is at most 0.012.
135. The formulation of any of Embodiments 131 to 135, wherein **R<sub>LL</sub>** is at least 0.0015.
136. The formulation of Embodiment 135, wherein **R<sub>LL</sub>** is at least 0.004.
137. The formulation of any previous Embodiment, wherein at least 85 weight% of the total polymer content (**Tpc**) within the formulation is a film-forming polymer.
138. The formulation of any previous Embodiment, wherein **Tpc** is at least 90 weight%.
139. The formulation of any previous Embodiment, wherein a first solvent weight ratio (**SWR1**) of **Hevap**, **HHevap**, and **LLevap** to the total amount of solvent **Ts** within the formulation,  

$$(\text{Hevap} + \text{HHevap} + \text{LLevap}) / \text{Ts}$$
is at least 0.6.
140. The formulation of Embodiment 139, wherein **SWR1** is at least 0.7.
141. The formulation of any previous Embodiment, wherein a relative solvent weight ratio (**RWSR**) of **LLevap** to a total **T<sub>H+HH</sub>** of **Hevap** and **HHevap** (**LLevap** / **T<sub>H+HH</sub>**) is at least 0.15:1.
142. The formulation of Embodiment 141, wherein **RWSR** is within a range of 0.15:1 to 2.2:1.
143. The formulation of Embodiment 141, wherein **RWSR** is within a range of 0.15:1 to 2:1.
144. The formulation of Embodiment 141, wherein **RWSR** is within a range of 0.15:1 to 1.8:1.
145. The formulation of any previous Embodiment, wherein a third weight ratio (**WR3**) of the non-volatile liquid softening agent to the resin (polymer) is at least 0.05:1.
146. The formulation of Embodiment 145, wherein **WR3** is at least 0.1:1.
147. The formulation of Embodiment 145, wherein **WR3** is at least 0.15:1.
148. The formulation of Embodiment 145, wherein **WR3** is at least 0.25:1.
149. The formulation of Embodiment 145, wherein **WR3** is at least 0.3:1.
150. The formulation of Embodiment 145, wherein **WR3** is at least 0.35:1.
151. The formulation of Embodiment 145, wherein **WR3** is at least 0.4:1.
152. The formulation of Embodiment 145, wherein **WR3** is at least 0.45:1.
153. The formulation of Embodiment 145, wherein **WR3** is at least 0.5:1.

154. The formulation of Embodiment 145, wherein **WR3** is at least 0.55:1.
155. The formulation of any of Embodiments 145 to 154, wherein **WR3** is at most 1.2:1.
155. The formulation of any of Embodiments 145 to 154, wherein **WR3** is at most 1.1:1.
155. The formulation of any of Embodiments 145 to 154, wherein **WR3** is at most 0.9:1.
155. The formulation of any of Embodiments 145 to 154, wherein **WR3** is at most 0.8:1.
155. The formulation of any of Embodiments 145 to 154, wherein **WR3** is at most 0.7:1.
156. The formulation of any previous Embodiment, wherein a fourth weight ratio (**WR4**) of the non-volatile liquid softening agent to the non-volatile content of the formulation is at least 0.15:1.
157. The formulation of Embodiment 156, wherein **WR4** is at least 0.2:1.
158. The formulation of Embodiment 156, wherein **WR4** is at least 0.25:1.
159. The formulation of Embodiment 156, wherein **WR4** is at least 0.3:1.
160. The formulation of Embodiment 156, wherein **WR4** is at least 0.35:1.
161. The formulation of Embodiment 156, wherein **WR4** is at least 0.4:1.
162. The formulation of Embodiment 156, wherein **WR4** is at least 0.45:1.
163. The formulation of Embodiment 156, wherein **WR4** is at least 0.5:1.
164. The formulation of any of Embodiments 156 to 163, wherein **WR4** is at most 0.7:1.
165. The formulation of Embodiment 164, wherein **WR4** is at most 0.6:1.
166. The formulation of any of Embodiments 156 to 163, wherein **WR4** is at most 0.55:1.
167. The formulation of any of Embodiments 156 to 162, wherein **WR4** is at most 0.5:1.
168. The formulation of any of Embodiments 156 to 161, wherein **WR4** is at most 0.45:1.
169. The formulation of any previous Embodiment, wherein a fifth weight ratio (**WR5**) of the photochromic dye to the non-volatile content of the ink formulation is at least 0.10:1.
170. The formulation of Embodiment 169, wherein **WR5** is at least 0.2:1.
171. The formulation of Embodiment 169, wherein **WR5** is at least 0.25:1.
172. The formulation of Embodiment 169, wherein **WR5** is at least 0.3:1.
173. The formulation of Embodiment 169, wherein **WR5** is at least 0.35:1.
174. The formulation of Embodiment 169, wherein **WR5** is at least 0.4:1.
175. The formulation of any of Embodiments 169 to 174, wherein **WR5** is at most 0.75:1.
176. The formulation of Embodiment 175, wherein **WR5** is at most 0.60:1.
177. The formulation of Embodiment 175, wherein **WR5** is at most 0.55:1.
178. The formulation of Embodiment 175, wherein **WR5** is at most 0.50:1.
179. The formulation of Embodiment 175, wherein **WR5** is at most 0.45:1.
180. An ink formulation comprising:
- (a) a resin;

- (b) a photochromic dye;
  - (c) a non-volatile liquid softening agent for softening the resin; and
  - (d) a solvent system including a very low vapor-pressure solvent **LLevap** and at least one of a high vapor-pressure solvent (**Hevap**) and a very high vapor-pressure solvent (**HHevap**);
- wherein the resin, the photochromic dye, and the non-volatile liquid softening agent are dissolved within the solvent system, forming a single liquid phase;
- wherein a first weight ratio (**WR1**) of the resin to the photochromic dye is at least 0.5:1;
- wherein a second weight ratio (**WR2**) of the non-volatile liquid softening agent to the photochromic dye is at least 0.15:1;
- wherein the non-volatile content of the ink formulation is within a range of 2.5 to 15%;
- wherein a first solvent weight ratio (**SWR1**) of **Hevap**, **HHevap**, and **LLevap** to the total amount of solvent **Ts** within the ink formulation,

$$(\text{Hevap} + \text{HHevap} + \text{LLevap}) / \text{Ts}$$

is at least 0.7;

and wherein a relative solvent weight ratio (**RWSR**) of **LLevap** to a total **T<sub>H+HH</sub>** of **Hevap** and **HHevap**, is within a range of 0.15:1 to 2.2:1.

- 181. The formulation of Embodiment 180 or any previous Embodiment, wherein **RWSR** is at least 0.20.
- 182. The formulation of Embodiment 181, wherein **RWSR** is at least 0.25.
- 183. The formulation of Embodiment 181, wherein **RWSR** is at least 0.30.
- 184. The formulation of Embodiment 181, wherein **RWSR** is at least 0.35.
- 185. The formulation of Embodiment 181, wherein **RWSR** is at least 0.45.
- 186. The formulation of Embodiment 181, wherein **RWSR** is at least 0.55.
- 187. The formulation of Embodiment 181, wherein **RWSR** is at least 0.65.
- 188. The formulation of Embodiment 181, wherein **RWSR** is at least 0.75.
- 189. The formulation of Embodiment 180 or any previous Embodiment, wherein **RWSR** is at most 2.0.
- 190. The formulation of Embodiment 189, wherein **RWSR** is at most 1.8.
- 191. The formulation of Embodiment 189, wherein **RWSR** is at most 1.6.
- 192. The formulation of Embodiment 189, wherein **RWSR** is at most 1.4.
- 193. The formulation of Embodiment 189, wherein **RWSR** is at most 1.2.
- 194. The formulation of Embodiment 189, wherein **RWSR** is at most 1.0.
- 195. The formulation of Embodiment 189, wherein **RWSR** is at most 0.85.
- 196. The formulation of any previous Embodiment, wherein **SWR1** is at least 0.75.
- 197. The formulation of Embodiment 196, wherein **SWR1** is at least 0.85.

198. The formulation of Embodiment 196, wherein **SWR1** is at least 0.92.
199. The formulation of Embodiment 196, wherein **SWR1** is at least 0.95.
200. The formulation of Embodiment 196, wherein **SWR1** is at least 0.98.
201. The formulation of any previous Embodiment, wherein a first total concentration of the group consisting of tetrahydrofuran (THF), methyl ethyl ketone (MEK), and acetone, by weight, is at most 12%.
202. The formulation of Embodiment 201, wherein the first total concentration is at most 8%.
203. The formulation of Embodiment 201, wherein the first total concentration is at most 4%.
204. The formulation of Embodiment 201, wherein the first total concentration is at most 1%.
205. The formulation of any previous Embodiment, wherein the water concentration, by weight, is at most 3%.
206. The formulation of Embodiment 205, wherein the water concentration is at most 1%.
207. The formulation of Embodiment 205, wherein the water concentration is at most 0.3%.
208. The formulation of any previous Embodiment, wherein the ethanol concentration, by weight, is at most 3%.
209. The formulation of Embodiment 208, wherein the water concentration is at most 1%.
210. The formulation of Embodiment 209, wherein a second total concentration (**TC2**) of the group consisting of glycerol, triacetin, propylene glycol, ethylene glycol, and polyethylene glycols, by weight, is at most 3%.
211. The formulation of Embodiment 210, wherein **TC2** is at most 2%.
212. The formulation of Embodiment 210, wherein **TC2** is at most 1%.
213. The formulation of Embodiment 210, wherein **TC2** is at most 0.5%.
214. The formulation of any previous Embodiment, wherein **LL<sub>evap</sub>** has a relative evaporation rate **R<sub>LL</sub>** of at most 0.08.
215. The formulation of Embodiment 214, wherein **R<sub>LL</sub>** is at most 0.06.
216. The formulation of Embodiment 214, wherein **R<sub>LL</sub>** is at most 0.04.
217. The formulation of Embodiment 214, wherein **R<sub>LL</sub>** is at most 0.03.
218. The formulation of Embodiment 214, wherein **R<sub>LL</sub>** is at most 0.02.
219. The formulation of any previous Embodiment, wherein **R<sub>LL</sub>** is at least 0.002.
220. The formulation of Embodiment 219, wherein **R<sub>LL</sub>** is at least 0.003.
221. The formulation of Embodiment 219, wherein **R<sub>LL</sub>** is at least 0.005.
222. The formulation of Embodiment 219, wherein **R<sub>LL</sub>** is at least 0.006.
223. The formulation of Embodiment 219, wherein **R<sub>LL</sub>** is at least 0.007.
224. The formulation of any previous Embodiment, wherein the ink formulation contains the high vapor-pressure solvent (**HH<sub>evap</sub>**).

225. The formulation of any previous Embodiment, wherein the ink formulation contains the very high vapor-pressure solvent (**Hevap**).

226. The formulation of any previous Embodiment, wherein **HHevap** has a relative evaporation rate **R<sub>HH</sub>** of at most 5.5.

227. The formulation of Embodiment 226, wherein **R<sub>HH</sub>** is at most 5.2.

228. The formulation of Embodiment 226, wherein **R<sub>HH</sub>** is at most 5.0.

229. The formulation of Embodiment 226, wherein **R<sub>HH</sub>** is at most 4.8.

230. The formulation of Embodiment 226, wherein **R<sub>HH</sub>** is at most 4.5.

231. The formulation of any previous Embodiment, wherein the softening agent forms a single liquid phase with the solvent system, the resin, and the photochromic dye.

#### METHOD EMBODIMENTS

1. A method of producing an optical construction on an optical substrate, the method comprising:

- (a) microvalving drops of a liquid ink formulation onto an optical surface of the optical substrate, to form a wet layer, the liquid ink formulation containing a photochromic dye;
- (b) treating the wet layer to produce a dried or cured photochromic dye containing layer on the optical surface;

wherein optionally, the optical surface is a curved surface, and wherein optionally, the optical surface is a polymeric surface, and where typically, the wet layer is a continuous wet layer.

2. The method of Embodiment 1, wherein the ink formulation is an organic or solvent-based ink formulation containing an organic or solvent-based solvent system.

3. The method of Embodiment 2, wherein the organic or solvent-based ink formulation further contains a polymer (resin) dissolved within the organic or solvent-based solvent system.

4. The method of Embodiment 3, wherein the organic or solvent-based solvent system contains a single liquid phase.

5. The method of any previous Embodiment, wherein the optical surface has the polymeric surface.

6. The method of any previous Embodiment, wherein the optical surface is the curved surface.

7. The method of Embodiment 6, wherein the SAG number of the optical substrate is defined by any of the features in system Embodiments 25 to 36.

8. The method of any previous Embodiment, wherein the base curve of the optical substrate is at least 2.

9. The method of Embodiment 8, wherein the base curve is at least 3.

10. The method of Embodiment 8, wherein the base curve is at least 4.

11. The method of Embodiment 8, wherein the base curve is at least 5.
12. The method of Embodiment 8, wherein the base curve is at least 6.
13. The method of Embodiment 8, wherein the base curve is at least 8.
14. The method of any previous Embodiment, wherein the base curve of the optical substrate is at most 14.
15. The method of Embodiment 14, wherein the base curve is at most 12.
16. The method of Embodiment 14, wherein the base curve is at most 10.
17. The method of any previous Embodiment, wherein for any point on the target surface, a an acute angle formed between (i) a plane that is tangent to the target surface at said given point and (ii) a horizontal plane is an angle ( $\alpha$ ), and wherein the maximum  $\alpha$  on the target surface is  $\alpha_{\max}$ , and wherein is  $\alpha_{\max}$  is at least  $5^{\circ}$ .
18. The method of Embodiment 17, wherein  $\alpha_{\max}$  is at least  $7^{\circ}$ .
19. The method of Embodiment 17, wherein  $\alpha_{\max}$  is at least  $10^{\circ}$ .
20. The method of Embodiment 17, wherein  $\alpha_{\max}$  is at least  $13^{\circ}$ .
21. The method of Embodiment 17, wherein  $\alpha_{\max}$  is at least  $16^{\circ}$ .
22. The method of Embodiment 17, wherein  $\alpha_{\max}$  is at least  $19^{\circ}$ .
23. The method of Embodiment 17, wherein  $\alpha_{\max}$  is at least  $23^{\circ}$ .
24. The method of Embodiment 17, wherein  $\alpha_{\max}$  is at least  $26^{\circ}$ .
25. The method of Embodiment 17, wherein  $\alpha_{\max}$  is at least  $31^{\circ}$ , at least  $34^{\circ}$ , or at least  $40^{\circ}$ .
26. The method of any of Embodiments 17 to 25, wherein  $\alpha_{\max}$  is at most  $50^{\circ}$ .
27. The method of Embodiment 26, wherein  $\alpha_{\max}$  is at most  $42^{\circ}$ .
28. The method of Embodiment 26, wherein  $\alpha_{\max}$  is at most  $37^{\circ}$ .
29. The method of any preceding Embodiment, wherein at least one of a thickness TH, characteristic thickness THc, and average thickness THav of the wet layer is at most 100 micrometers ( $\mu\text{m}$ ).
30. The method of Embodiment 29, wherein at least one of TH, THc and THav is at most  $80\mu\text{m}$ .
31. The method of Embodiment 29, wherein at least one of TH, THc and THav is at most  $70\mu\text{m}$ .
32. The method of Embodiment 29, wherein at least one of TH, THc and THav is at most  $60\mu\text{m}$ .
33. The method of Embodiment 29, wherein at least one of TH, THc and THav is at most  $50\mu\text{m}$ .
34. The method of any of Embodiments 29 to 33, wherein at least one of TH, THc, and THav is at least  $10\mu\text{m}$ .
35. The method of Embodiment 34, wherein at least one of TH, THc, and THav is at least  $18\mu\text{m}$ .
36. The method of Embodiment 34, wherein at least one of TH, THc, and THav is at least  $25\mu\text{m}$ .
37. The method of Embodiment 34, wherein at least one of TH, THc, and THav is at least  $30\mu\text{m}$ .

38. The method of Embodiment 34, wherein at least one of TH, THc, and THav is at least 35 $\mu$ m.
39. The method of Embodiment 34, wherein at least one of TH, THc, and THav is at least 40 $\mu$ m.
40. The method of Embodiment 34, wherein at least one of TH, THc, and THav is at least 45 $\mu$ m.
41. The method of any of Embodiments 29 to 40, wherein at least one of TH, THc, and THav includes TH.
42. The method of any of Embodiments 29 to 40, wherein at least one of TH, THc, and THav includes THav.
43. The method of any of Embodiments 29 to 40, wherein at least one of TH, THc, and THav includes TH and THav.
44. The method of any of Embodiments 29 to 40, wherein at least one of TH, THc, and THav includes TH, THc, and THav.
45. The method of any of Embodiments 29 to 38 and 41 to 44, wherein at least one of TH, THc and THav is at most 40 $\mu$ m.
46. The method of any of Embodiments 29 to 36 and 41 to 44, wherein at least one of TH, THc and THav is at most 30 $\mu$ m.
47. The method of any of Embodiments 29 to 46, wherein at least one of TH, THc, and THav is at least 4 $\mu$ m.
48. The method of Embodiment 47, wherein at least one of TH, THc and THav is at least 5.5 $\mu$ m.
49. The method of Embodiment 47, wherein at least one of TH, THc, and THav is at least 7 $\mu$ m.
50. The method of any preceding Embodiment, wherein, with respect to the ink drops, at least one of a drop volume Vd a characteristic drop volume Vd-c, and an average drop volume Vd-av is within a range of 4 to 400 nanoliters (nl).
51. The method of Embodiment 50, wherein at least one of Vd, Vd-c and Vd-av is at least 5nl.
52. The method of Embodiment 50, wherein at least one of Vd, Vd-c and Vd-av is at least 6nl.
53. The method of Embodiment 50, wherein at least one of Vd, Vd-c and Vd-av is at least 8nl.
54. The method of Embodiment 50, wherein at least one of Vd, Vd-c and Vd-av is at least 10nl.
55. The method of Embodiment 50, wherein at least one of Vd, Vd-c and Vd-av is at least 12nl.
56. The method of Embodiment 50, wherein at least one of Vd, Vd-c and Vd-av is at least 15nl.
57. The method of any of Embodiments 50 to 56, wherein at least one of Vd, Vd-c and Vd-av is at most 250nl.
58. The method of Embodiment 57, wherein at least one of Vd, Vd-c and Vd-av is at most 100nl.
59. The method of Embodiment 57, wherein at least one of Vd, Vd-c and Vd-av is at most 70nl.
60. The method of Embodiment 57, wherein at least one of Vd, Vd-c and Vd-av is at most 50nl.
61. The method of Embodiment 57, wherein at least one of Vd, Vd-c and Vd-av is at most 45nl.
62. The method of Embodiment 57, wherein at least one of Vd, Vd-c and Vd-av is at most 40nl.

63. The method of Embodiment 57, wherein at least one of Vd, Vd-c and Vd-av is at most 35nl.
64. The method of Embodiment 57, wherein at least one of Vd, Vd-c and Vd-av is at most 30nl.
65. The method of Embodiment 57, wherein at least one of Vd, Vd-c and Vd-av is at most 25nl.
66. The method of Embodiment 57, wherein at least one of Vd, Vd-c and Vd-av is at most 22nl.
67. The method of Embodiment 57, wherein at least one of Vd, Vd-c and Vd-av is at most 20nl.
68. The method of Embodiment 57, wherein at least one of Vd, Vd-c and Vd-av is at most 18nl.
69. The method of Embodiment 57, wherein at least one of Vd, Vd-c and Vd-av is at most 16nl.
70. The method of any preceding Embodiment, wherein the polymeric surface is or includes a thermoset polymer, the polymeric surface optionally coated with a hardcoat.
71. The method of Embodiment 70, wherein the polymeric surface is coated with the hardcoat.
72. The method of Embodiment 70 or 71, wherein the thermoset polymer is a urethane-based thermoset polymer such as Trivex<sup>®</sup>.
73. The method of Embodiment 70 or 71, wherein the thermoset polymer is made from allyl diglycol carbonate, such as CR-39<sup>®</sup>.
74. The method of any preceding Embodiment, wherein the polymeric surface is or includes a thermoplastic polymer, the polymeric surface optionally coated with a hardcoat.
75. The method of Embodiment 74, wherein the polymeric surface is coated with the hardcoat.
76. The method of Embodiment 74 or 75, wherein the thermoplastic polymer is a polycarbonate.
77. The method of any preceding Embodiment, further comprising, prior to the microvalving ink drops of the ink formulation, subjecting the optical surface of the optical substrate to at least one surface treatment.
78. The method of Embodiment 77, wherein the at least one surface treatment includes an energy treatment for raising the surface energy of the optical surface.
79. The method of Embodiment 78, wherein the energy treatment includes at least one energy treatment selected from the group consisting of corona, plasma, electron beam, electrical discharge, and actinic radiation treatments.
80. The method of any of Embodiments 77 to 79, wherein the surface (energy) treatment raises the surface energy of the optical substrate by at least 2 mN/m, at least 3 mN/m, at least 5 mN/m, at least 8 mN/m, or at least 12 mN/m.
81. The method of any of Embodiments 77 to 80, wherein the surface treatment raises the surface energy of the optical substrate by at most 40 mN/m, at most 30 mN/m, at most 20 mN/m, or at most 14 mN/m.
82. The method of any of Embodiments 77 to 81, wherein the surface treatment includes applying a primer to a first surface of the optical substrate to form a wet primer coating, and allowing the wet primer coating to dry to form the optical surface of the optical substrate.

83. The method of any of Embodiments 77 to 81, wherein the surface treatment includes applying a primer to a first surface of the optical substrate to form a wet primer coating, and curing the wet primer coating to form the optical surface of the optical substrate.
84. The method of Embodiment 82, wherein the curing the wet primer coating produces a fully-cured primer coating, prior to applying the wet (photochromic) layer.
85. The method of Embodiment 83, wherein the fully-cured primer coating has a hardness coefficient ( $C_H$ ) of at least 0.9 or at least 0.95.
86. The method of Embodiment 83 or 84, wherein the cured primer coating has a non-tacky upper surface.
87. The method of any of Embodiments 218 to 220, wherein the cured primer coating has a thickness ( $T_p$ ) of at least  $0.4\mu\text{m}$ .
88. The method of Embodiment 87, wherein  $T_p$  is at least  $0.6\mu\text{m}$ .
89. The method of Embodiment 87, wherein  $T_p$  is at least  $0.8\mu\text{m}$ .
90. The method of Embodiment 87, wherein  $T_p$  is at least  $1.0\mu\text{m}$ .
91. The method of any of Embodiments 87 to 90, wherein  $T_p$  is at most  $3\mu\text{m}$ .
92. The method of Embodiment 91, wherein  $T_p$  is at most  $2.5\mu\text{m}$ .
93. The method of Embodiment 91, wherein  $T_p$  is at most  $2.0\mu\text{m}$ .
94. The method of Embodiment 91, wherein  $T_p$  is at most  $1.7\mu\text{m}$ .
95. The method of Embodiment 91, wherein  $T_p$  is at most  $1.4\mu\text{m}$ .
96. The method of any of Embodiments 87 to 95, wherein  $T_p$  is at least one of a local thickness and an average thickness.
97. The method of any previous Embodiment, wherein a or the energy treatment is applied to the top surface of the cured or fully-cured primer coating.
98. The method of any of Embodiments 78 to 97, wherein the energy treatment is applied to the exposed surface of the optical substrate, prior to applying the primer.
99. The method of any preceding Embodiment, wherein the energy treatment is applied to the top surface of the dried (fully cured) photochromic dye containing layer, prior to applying the overcoat layer.
100. The method of any preceding Embodiment, wherein the energy treatment is applied to the top surface of the dried (fully cured) overcoat layer, prior to applying the hardcoat layer.
101. The method of any preceding Embodiment, further comprising, after treating the wet layer to produce a dried dye-containing layer on the optical surface, applying a wet overcoat layer on top of the outer or exposed face of the dried dye-containing layer.
102. The method of Embodiment 101, wherein the overcoat layer includes polyvinyl butyral.

103. The method of Embodiment 101 or 102, further comprising curing the overcoat layer to produce a fully-cured overcoat layer.
104. The method of Embodiment 103, wherein the fully-cured overcoat layer has a thickness (**T<sub>ov</sub>**) of at least 4 $\mu$ m.
105. The method of Embodiment 103, wherein **T<sub>ov</sub>** is at least 6 $\mu$ m.
106. The method of Embodiment 103, wherein **T<sub>ov</sub>** is at least 7 $\mu$ m.
107. The method of Embodiment 103, wherein **T<sub>ov</sub>** is at least 7.5 $\mu$ m.
108. The method of any of Embodiments 104 to 107, wherein **T<sub>ov</sub>** is at most 18 $\mu$ m.
109. The method of Embodiment 108, wherein **T<sub>ov</sub>** is at most 15 $\mu$ m.
110. The method of Embodiment 108, wherein **T<sub>ov</sub>** at most 13 $\mu$ m.
111. The method of Embodiment 108, wherein **T<sub>ov</sub>** is at most 12 $\mu$ m.
112. The method of Embodiment 105, wherein **T<sub>ov</sub>** is at most 11 $\mu$ m.
113. The method of any of Embodiments 105 to 112, wherein **T<sub>ov</sub>** is at least one of a local thickness and an average thickness.
114. The method of any preceding Embodiment, applying a first liquid hardcoat formulation onto a currently exposed optical surface of the optical substrate, to form a first wet hardcoat layer.
115. The method of Embodiment 114, wherein the currently exposed optical surface is a or the fully cured overcoat layer.
116. The method of Embodiment 114 or 115, further comprising curing the first wet hardcoat layer to form a first fully cured hardcoat layer.
117. The method of Embodiment 116, wherein a thickness **T<sub>h</sub>** of the first fully cured hardcoat layer is at least 1.2 $\mu$ m.
118. The method of Embodiment 117, wherein **T<sub>h</sub>** is at least 1.5 $\mu$ m.
119. The method of Embodiment 117, wherein **T<sub>h</sub>** is at least 1.8 $\mu$ m.
120. The method of any of Embodiments 116 to 118, wherein **T<sub>h</sub>** is at most 8.0.
121. The method of Embodiment 119, wherein **T<sub>h</sub>** is at most 6 $\mu$ m.
122. The method of Embodiment 119, wherein **T<sub>h</sub>** is at most 4.5 $\mu$ m.
123. The method of Embodiment 119, wherein **T<sub>h</sub>** is at most 3.5 $\mu$ m.
124. The method of Embodiment 119, wherein **T<sub>h</sub>** is at most 3 $\mu$ m.
125. The method of Embodiment 119, wherein **T<sub>h</sub>** is at most 2.7 $\mu$ m.
126. The method of Embodiment 119, wherein **T<sub>h</sub>** is at most 2.4 $\mu$ m.
127. The method of Embodiment 119, wherein **T<sub>h</sub>** is at most 2.2 $\mu$ m.
128. The method of Embodiment 119, wherein **T<sub>h</sub>** is at most 2 $\mu$ m.

129. The method of any of Embodiments 117 to 128, wherein  $T_h$  is at least one (and typically both) of a local thickness and an average thickness.
130. The method of any of Embodiments 117 to 118 and 123 to 129, wherein the currently exposed optical surface is a or the fully cured overcoat layer.
131. The method of any of the preceding Embodiments, wherein a thickness  $T_{PC}$  of the dried photochromic dye containing layer is at least  $1.2\mu m$ .
132. The method of Embodiment 131, wherein  $T_{PC}$  is at least  $1.6\mu m$ .
133. The method of Embodiment 131, wherein  $T_{PC}$  is at least  $2\mu m$ .
134. The method of Embodiment 131, wherein  $T_{PC}$  is at least  $2.4\mu m$ .
135. The method of Embodiment 131, wherein  $T_{PC}$  is at least  $2.7\mu m$ .
136. The method of any of Embodiments 131 to 135, wherein  $T_{PC}$  is at most  $5.5\mu m$ .
137. The method of Embodiment 136, wherein  $T_{PC}$  is at most  $5\mu m$ .
138. The method of Embodiment 136, wherein  $T_{PC}$  is at most  $4.6\mu m$ .
139. The method of Embodiment 136, wherein  $T_{PC}$  is at most  $4.2\mu m$ .
140. The method of Embodiment 136, wherein  $T_{PC}$  is at most  $3.8\mu m$ .
141. The method of any of Embodiments 131 to 140, wherein  $T_{PC}$  is at least one of a local thickness and an average thickness.
142. The method of any of Embodiments 114 to 141, further comprising applying a second liquid hardcoat formulation onto a currently exposed optical surface of the optical substrate, to form a second wet hardcoat layer.
143. The method of Embodiment 142, further comprising curing the second wet hardcoat layer to form a second cured hardcoat layer.
144. The method of any preceding Embodiment, wherein the optical surface is an ophthalmic surface.
145. The method of any preceding Embodiment, wherein the optical substrate is an ophthalmic substrate.
146. The method of Embodiments 144 or 145, wherein the optical surface or ophthalmic surface is the front surface of the substrate.
147. The method of Embodiments 144 or 145, wherein the optical surface or ophthalmic surface is the back surface of the substrate.
148. The method of any of Embodiments 144 or 147, wherein the optical surface or ophthalmic surface is a convex surface.
149. The method of any of Embodiments 144 or 147, wherein the optical surface or ophthalmic surface is a concave surface.

150. The method of any preceding Embodiment, wherein the direction of the relative movement between the nozzle of the microvalving apparatus and the optical substrate is in the XY plane of the optical substrate.
151. The method of any preceding Embodiment, wherein the direction of the relative movement between the nozzle of the microvalving apparatus and the optical substrate is limited to the XY plane of the optical substrate.
152. The method of any preceding Embodiment, wherein, during the microvalving, the distance ( **$\Delta D_{jet}$** ) between the nozzle of the microvalving apparatus and the optical substrate varies by at least 0.5mm, due to the curvature of the optical substrate.
153. The method of Embodiment 152, wherein  **$\Delta D_{jet}$**  is at least 1.0mm.
154. The method of Embodiment 152, wherein  **$\Delta D_{jet}$**  is at least 2mm.
155. The method of Embodiment 152, wherein  **$\Delta D_{jet}$**  is at least 3.5mm.
156. The method of any of Embodiments 152 to 155, wherein  **$\Delta D_{jet}$**  is at most 15mm.
157. The method of any preceding Embodiment, wherein, during the microvalving, the distance between the nozzle of the microvalving apparatus and the optical substrate is uncontrolled.
158. The method of any preceding Embodiment, wherein, within the printed area, an average (mean) calculated thickness of dye on the optical substrate is at least 0.2 $\mu$ m.
159. The method of Embodiment 158, wherein the average calculated thickness of dye on the optical substrate is at least 0.3 $\mu$ m.
160. The method of Embodiment 158, wherein the average calculated thickness of dye on the optical substrate is at least 0.4 $\mu$ m.
161. The method of Embodiment 158, wherein the average calculated thickness of dye on the optical substrate is at least 0.5 $\mu$ m.
162. The method of any of Embodiments 158 to 161, wherein the average calculated thickness of dye on the optical substrate is at most 2 $\mu$ m.
163. The method of Embodiment 162, wherein the average calculated thickness of dye on the optical substrate is at most 1.5 $\mu$ m.
164. The method of Embodiment 162, wherein the average calculated thickness of dye on the optical substrate is at most 1.2 $\mu$ m.
165. The method of Embodiment 162, wherein the average calculated thickness of dye on the optical substrate is at most 1.0 $\mu$ m.
166. The method of Embodiment 162, wherein the average calculated thickness of dye on the optical substrate is at most 0.9 $\mu$ m.

167. The method of Embodiment 162, wherein the average calculated thickness of dye on the optical substrate is at most 0.8 $\mu$ m.
168. The method of Embodiment 162, wherein the average calculated thickness of dye on the optical substrate is at most 0.7 $\mu$ m.
169. The method of Embodiment 162, wherein the average calculated thickness of dye on the optical substrate is at most 0.6 $\mu$ m.
170. The method of any preceding Embodiment, wherein the treating of the wet layer to produce a dried dye-containing layer is performed after at most 3 of the wet layers have been microvalved.
171. The method of any preceding Embodiment, wherein the treating of the wet layer to produce a dried dye-containing layer is performed after at most 2 of the wet layers have been microvalved.
172. The method of any preceding Embodiment, wherein the treating of the wet layer to produce a dried dye-containing layer is performed after a single wet layer of the wet layer has been microvalved.
173. The method of any preceding Embodiment, wherein the optical construction has a single dye layer containing the dye.
174. The method of any preceding Embodiment, wherein the entire thickness **Toc** of the optical construction is within a range of 3 to 50 $\mu$ m, 5 to 50 $\mu$ m, or 8 to 50 $\mu$ m.
175. The method of Embodiment 174, wherein **Toc** is at least 10 $\mu$ m.
176. The method of Embodiment 174, wherein **Toc** is at least 12 $\mu$ m.
177. The method of Embodiment 174, wherein **Toc** is at least 15 $\mu$ m.
178. The method of any of Embodiments 174 to 177, wherein **Toc** is at most 40 $\mu$ m, at most 30 $\mu$ m, at most 25 $\mu$ m, at most 20 $\mu$ m, or at most 16 $\mu$ m.
179. The method of any preceding Embodiment, wherein the optical substrate has a diameter of at least 40mm.
180. The method of any preceding Embodiment, wherein the optical substrate has a diameter of at least 50mm.
181. The method of any preceding Embodiment, wherein the optical substrate has a diameter of at least 60mm.
182. The method of any preceding Embodiment, wherein the optical substrate has a diameter of at least 70mm.
183. The method of any preceding Embodiment, wherein the optical substrate has a diameter of at least 80mm.

184. The method of any preceding Embodiment, wherein the optical substrate has a diameter of at most 90mm.
185. The method of any preceding Embodiment, wherein the optical substrate has a diameter within a range of 50mm to 80mm.
186. The method of any preceding Embodiment, wherein the optical substrate is a lens blank.
187. The method of Embodiment 186, wherein the lens blank is semi-finished.
188. The method of Embodiment 186, wherein the lens blank is finished.
189. The method of any preceding Embodiment, wherein the optical substrate is a lens (e.g., an edged lens).
190. The method of any preceding Embodiment, further comprising mounting the optical substrate having the dried dye-containing layer into eyeglasses frames (e.g. as a lens thereof).
191. The method of any preceding Embodiment, wherein the softening agent for softening the resin is distributed evenly or homogeneously within the wet photochromic layer.
191. The method of any preceding Embodiment, wherein the liquid ink formulation is the ink formulation of any one of formulation Embodiments 1 to 231.
192. The method of any preceding Embodiment, the method utilizing any feature or features of the ink formulation of any one of formulation Embodiments 1 to 231.
193. The method of any preceding Embodiment, the method utilizing any feature or features of the features provided in the formulation Embodiments.
194. The method of any preceding Embodiment, the method utilizing any feature or features of the features provided in the system Embodiments hereinbelow.
195. The method of any preceding Embodiment, the method utilizing any feature or features as described herein.

#### OPTICAL CONSTRUCTION EMBODIMENTS

1. An optical construction, as described herein.
2. An optical construction comprising any of the structural features disclosed in method Embodiments 1 to 195.
3. An optical construction comprising any of the structural features disclosed in system Embodiments 1 to 72.
3. The optical construction of any of Embodiments 1 to 3, wherein the optical construction is or includes an eyeglass lens.
4. Eyeglasses comprising an eyeglass frame and at least one eyeglass lens of Embodiment 4.

SYSTEM EMBODIMENTS

1. A coating system comprising:
  - (a) a photochromic-ink-formulation-application station including microvalve apparatus configured to microvalve droplets of a photochromic-ink-formulation onto a target surface of an optical substrate to form a wet layer on the target surface; and
  - (b) a drying and/or curing station configured to dry and/or cure the wet layer to produce a cured coating on the target surface.
2. The system of Embodiment 1, further comprising:
  - (c) an optical-substrate transfer apparatus configured to transfer the optical substrate having the wet layer on the target surface thereof from the photochromic-ink-formulation-application station to the drying and/or curing station.
3. The system of Embodiment 1 or 2, wherein the optical-substrate-transfer apparatus includes at least one of a robotic arm, a gripper, a conveyer belt, and an elevator for raising or lowering an elevation of the optical substrate on the target surface thereof.
4. The system of any previous Embodiment, further comprising a controller programmed or programmable to regulate the optical-substrate-transfer apparatus such that the transfer of the optical substrate is contingent upon a detection that the wet layer has been formed on the target surface of the optical substrate at the photochromic-ink-formulation-application station.
5. The system of any previous Embodiment, wherein the drying and/or curing station includes at least one of a heat lamp, an oven, and a UV-curing mechanism.
6. The system of any previous Embodiment, wherein the drying and/or curing station includes an oven which: (i) is open when the optical substrate having the wet layer on the target surface thereof is transferred thereinto, and (ii) is closed, subsequent to transfer of the optical substrate to the oven, and remains closed during the drying and/or curing.
7. The system of any previous Embodiment, comprising a primer application station configured to apply droplets of a primer formulation onto the target surface before microvalving photochromic-ink-formulation thereupon.
8. The system of Embodiment 7, wherein the primer application station includes a microvalve apparatus for applying drops of the primer formulation.
9. The system of any previous Embodiment, further comprising at least one of: (i) a treatment station for increasing the surface energy of the target surface before application thereon of the primer or the photochromic ink formulation; and (ii) a cleaning station for subjecting the target surface to a cleaning process before microvalve-application thereon of the primer or the photochromic ink formulation.

10. The system of Embodiment 9, further comprising the surface energy treatment station, said surface energy station including at least one of a corona-treatment-apparatus and a plasma-treatment apparatus.
11. The system of any preceding Embodiment, wherein the photochromic-ink-formulation-application station includes a reservoir of the photochromic ink formulation and is configured to microvalve, onto the target surface of the optical substrate, photochromic ink formulation stored in the reservoir.
12. The system of any preceding Embodiment, wherein the system is further configured to apply, optionally by microvalving, at least one of a tint formulation and an additional photochromic formulation to the target surface of the optical substrate before the application thereon of the wet layer of the photochromic ink formulation.
13. The system of any preceding Embodiment, wherein the system is devoid of dip coating apparatus.
14. The system of any preceding Embodiment, wherein the system is devoid of spin coating apparatus.
15. The system of any preceding Embodiment, including a controller configured or programmed to control the microvalving of the droplets of the formulation onto the target surface.
16. The system of any one of the preceding Embodiments, wherein the target surface is curved.
17. The system of any one of the preceding Embodiments, wherein the target surface has a SAG number of at least 0.5mm.
18. The system of any one of Embodiments 15 to 17, wherein the controller is configured or programmed to control the microvalving such that a ratio of a volume of formulation applied per unit of area of a two-dimensional projection of the target surface is constant.
19. The system of any one of Embodiments 15 to 17, wherein the controller is configured or programmed to control the microvalving such that a ratio of a volume of formulation applied per unit of area of a two-dimensional projection of the target surface, within any subdivision of said two-dimensional projection having an area of 5% or more of an area of the projection, is within  $\pm 10\%$ , or within  $\pm 5\%$ , or within  $\pm 2\%$ , or within  $\pm 1\%$  of a mean value of said ratio for all of said two-dimensional projection.
20. The system of any one of Embodiments 15 to 19, wherein the controller is configured or programmed to generate the two-dimensional projection of the target surface, before the microvalving.
21. The system of any one of Embodiments 15 to 20, wherein the controller is configured or programmed to calculate or select a ratio of the volume of formulation per unit of area of the two-dimensional projection of the target surface, before the microvalving.

22. The system of Embodiment 21, wherein the controller is configured or programmed to control the microvalving such that a ratio of a volume of formulation applied per unit of area of a two-dimensional projection of the target surface, within any subdivision of said two-dimensional projection having an area of 5% or more of an area of the projection, is within  $\pm 10\%$ , or within  $\pm 5\%$ , or within  $\pm 2\%$ , or within  $\pm 1\%$  of said calculated or selected ratio.
23. The system of any preceding Embodiment, wherein the microvalving is such that a ratio of a mean volume of formulation applied per unit of area of the target surface in an edge portion thereof characterized by lying between 90% and 100% of a distance from a centroid of the target surface and a perimeter thereof, is between 0.60 and 0.96 times a maximum ratio of a volume of formulation applied per unit of area of the target surface.
24. The system of any of Embodiments 1 to 22, wherein the microvalving is such that a ratio of a mean volume of formulation applied per unit of area of the target surface in an edge portion thereof characterized by lying between 90% and 100% of a distance from a centroid of the target surface and a perimeter thereof, is between 0.60 and 0.96 times a mean ratio of a volume of formulation applied per unit of area in a central area characterized by lying between 0% and 10% of a distance from said centroid of the target surface and said perimeter.
25. The system of either one of Embodiments 23 or 24, wherein the SAG number of the target surface is at least 1mm and at most 15mm.
26. The system of Embodiment 25, wherein the SAG number is at least 2mm.
27. The system of Embodiment 25, wherein the SAG number is at least 3.5mm.
28. The system of Embodiment 25, wherein the SAG number is at least 4.5mm.
29. The system of Embodiment 25, wherein the SAG number is at least 5mm.
30. The system of Embodiment 25, wherein the SAG number is at least 6mm.
31. The system of Embodiment 25, wherein the SAG number is at least 7mm.
32. The system of Embodiment 25, wherein the SAG number is at least 9mm.
33. The system of any of Embodiments 25 to 32, wherein the SAG number is at most 13.5mm.
34. The system of Embodiment 33, wherein the SAG number is at most 12mm.
35. The system of Embodiment 33, wherein the SAG number is at most 10.5mm.
36. The system of any of Embodiments 25 to 31, wherein the SAG number is at most 8mm.
37. The system of any one of Embodiments 23 to 36, wherein the ratio in the edge portion is between 0.6 and 0.9 times the maximum ratio.
38. The system of any one of Embodiments 23 to 36, wherein the ratio in the edge portion is between 0.6 and 0.85 times the maximum ratio.
39. The system of any one of Embodiments 23 to 36, wherein the ratio in the edge portion is between 0.8 and 0.96 times the ratio in the central area.

40. The system of any one of Embodiments 23 to 36, wherein the ratio in the edge portion is between 0.9 and 0.96 times the ratio in the central area.
41. The system of any one of Embodiments 13 to 22, wherein the SAG number of the target surface is between 9mm and 13mm, and the microvalving is such that a ratio of a volume of formulation applied per unit of area of the target surface near an edge thereof characterized by lying between 90% and 100% of a distance from a centroid of the target surface and a perimeter thereof, is between 0.62 and 0.85 times a maximum ratio of a volume of formulation applied per unit of area of the target surface.
42. The system of any one of Embodiments 13 to 22, wherein the SAG number of the target surface is between 7mm and 9mm, and the microvalving is such that a ratio of a volume of formulation applied per unit of area of the target surface near an edge thereof characterized by lying between 90% and 100% of a distance from a centroid of the target surface and a perimeter thereof, is between 0.72 and 0.92 times a maximum ratio of a volume of formulation applied per unit of area of the target surface.
43. The system of any one of Embodiments 13 to 22, wherein the SAG number of the target surface is between 5mm and 7mm, and the microvalving is such that a ratio of a volume of formulation applied per unit of area of the target surface near an edge thereof characterized by lying between 90% and 100% of a distance from a centroid of the target surface and a perimeter thereof, is between 0.82 and 0.96 times a maximum ratio of a volume of formulation applied per unit of area of the target surface.
44. The system of any one of Embodiments 13 to 22, wherein the microvalving is such that a ratio of a mean volume of formulation applied per unit of area of the target surface at a given point on the target surface, is equal to a reduction factor times a maximum ratio of a volume of formulation applied per unit of area at any point on the target surface, said reduction factor being equal to a cosine of an acute angle formed between (i) a plane that is tangent to the target surface at said given point and (ii) a horizontal plane.
45. The system of Embodiment 44, wherein the reduction factor at any point on a perimeter of the curved surface is between 0.63 and 0.96.
46. The system of any one of Embodiments 13 to 45, wherein for any point on the target surface, a maximum acute angle formed between (i) a plane that is tangent to the target surface at said given point and (ii) a horizontal plane is between 10° and 40°.
47. The system of any one of Embodiments 13 to 45, wherein for any point on the target surface, a maximum acute angle formed between (i) a plane that is tangent to the target surface at said given point and (ii) a horizontal plane is between 5° and 50°.

48. The system of any one of Embodiments 13 to 45, wherein for any point on the target surface, a maximum acute angle formed between (i) a plane that is tangent to the target surface at said given point and (ii) a horizontal plane is between 15° and 40°.
49. The system of any one of Embodiments 13 to 45, wherein for any point on the target surface, a maximum acute angle formed between (i) a plane that is tangent to the target surface at said given point and (ii) a horizontal plane is between 5° and 20°.
50. The system of any one of the preceding Embodiments, wherein the system is configured to perform the microvalving without any relative vertical *z*-axis movement between the microvalve apparatus and the target surface.
51. The system of any one of the preceding Embodiments, wherein the system is not configured to perform the microvalving while causing relative vertical *z*-axis movement between the microvalve apparatus and the target surface.
52. The system of any one of the preceding Embodiments, wherein the system is not configured to perform the microvalving while causing relative vertical *z*-axis movement between the microvalve apparatus and the target surface.
53. The system of any one of the preceding Embodiments, wherein the system is configured to perform the microvalving without any relative rotational movement on a horizontal *x*-*y* plane between the microvalve apparatus and the target surface during the forming of the wet layer.
54. The system of any one of the preceding Embodiments, wherein the system is not configured to perform the microvalving while causing relative rotational movement on a horizontal *x*-*y* plane between the microvalve apparatus and the target surface during the forming of the wet layer.
55. The system of Embodiment 54, wherein the photochromic-ink-formulation-application station comprises a non-rotating optical-substrate holder.
56. The system of any of preceding Embodiment, wherein the microvalve apparatus is piezo-actuated.
57. The system of any of Embodiments 1 to 55, wherein the microvalve apparatus is electromagnetically actuated.
58. The system of any of preceding Embodiment, wherein for any point on the target surface, an acute angle formed between (i) a plane that is tangent to the target surface at said given point and (ii) a horizontal plane, is an angle ( $\alpha$ ), wherein the maximum  $\alpha$  on the target surface is  $\alpha_{\max}$ , and wherein  $\alpha_{\max}$  is at least 5°.
59. The system of Embodiment 58, wherein  $\alpha_{\max}$  is at least 10°.
60. The system of Embodiment 58, wherein  $\alpha_{\max}$  is at least 15°.
61. The system of Embodiment 58, wherein  $\alpha_{\max}$  is at least 20°.

62. The system of Embodiment 58, wherein  $\alpha_{\max}$  is at least  $25^\circ$ .
63. The system of Embodiment 58, wherein  $\alpha_{\max}$  is at least  $30^\circ$ .
64. The system of any one of claims 2-4, wherein  $\alpha_{\max}$  is at most  $50^\circ$ .
65. The system of any one of Embodiments 58 to 64, wherein  $\alpha_{\max}$  is within a range of  $30-40^\circ$ , and wherein  $R_{D1}$  is at most 0.90, or within a range of 0.62 to 0.90.
66. The system of any one of Embodiments 58 to 64, wherein  $\alpha_{\max}$  is within a range of  $19-27^\circ$ , and wherein  $R_{D1}$  is at most 0.93, or within a range of 0.85 to 0.93.
67. The system of any one of Embodiments 58 to 64, wherein  $\alpha_{\max}$  is within a range of  $15-20^\circ$ , and wherein  $R_{D1}$  is at most 0.97 or within a range of 0.90 to 0.97.
68. The system of any preceding Embodiment, wherein the liquid ink formulation is the ink formulation of any one of formulation Embodiments 1 to 231.
69. The system of any preceding Embodiment, the system comprising any feature or features of the ink formulation of any one of formulation Embodiments 1 to 231.
70. The system of any preceding Embodiment, the system comprising any feature or features of the features provided in the formulation Embodiments.
71. The system of any preceding Embodiment, the system comprising any feature or features of the features provided in the method Embodiments hereinabove.
72. The system of any preceding Embodiment, the system comprising any feature or features as described herein.

It will be appreciated that certain features of the invention, which are, for clarity, described in the context of separate embodiments, may also be provided in combination in a single embodiment. Conversely, various features of the invention, which are, for brevity, described in the context of a single embodiment, may also be provided separately or in any suitable sub-combination.

Although the invention has been described in conjunction with specific embodiments thereof, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art. Accordingly, it is intended to embrace all such alternatives, modifications and variations that fall within the spirit and broad scope of the appended claims. All publications, patents and patent applications mentioned in this specification are herein incorporated in their entirety by reference into the specification, to the same extent as if each individual publication, patent or patent application was specifically and individually indicated to be incorporated herein by reference. In addition, citation or identification of any reference in this application shall not be construed as an admission that such reference is available as prior art to the present invention.

## WHAT IS CLAIMED IS

## 1. A coating system comprising:

- (a) a photochromic-ink-formulation-application station including microvalve apparatus configured to microvalve droplets of a photochromic-ink-formulation onto a target surface of an optical substrate to form a wet layer on the target surface;
- (b) a drying and/or curing station configured to dry and/or cure, on the target surface, the wet layer to produce a cured coating thereof;
- (c) an optical-substrate transfer apparatus configured to transfer the optical substrate having the wet layer on the target surface thereof from the photochromic-ink-formulation-application station to the drying and/or curing station; and
- (d) a treatment station for increasing the surface energy of the target surface before application thereon of the primer; and
- (e) a controller configured or programmed to control the microvalving of the droplets of the formulation onto the target surface;

wherein the microvalving is such that a dimensionless ink coverage ratio ( $R_{D1}$ ) defined by a ratio of a mean volume of formulation applied per unit of area of the target surface in an edge portion thereof characterized by lying between 90% and 100% of a distance from a centroid of the target surface and a perimeter thereof, is between 0.60 and 0.96 times a mean ratio of a volume of formulation applied per unit of area in a central area characterized by lying between 0% and 10% of a distance from said centroid of the target surface and said perimeter.

2. The system of claim 1, wherein for any point on the target surface, an acute angle formed between (i) a plane that is tangent to the target surface at said given point and (ii) a horizontal plane, is an angle ( $\alpha$ ), wherein the maximum  $\alpha$  on the target surface is  $\alpha_{max}$ , and wherein  $\alpha_{max}$  is at least  $5^\circ$ .

3. The system of claim 2, wherein  $\alpha_{max}$  is at least  $10^\circ$ .

4. The system of claim 2, wherein  $\alpha_{max}$  is at least  $15^\circ$ .

5. The system of any one of claims 2-4, wherein  $\alpha_{max}$  is at most  $50^\circ$ .

6. The system of any one of claims 2-4, wherein  $\alpha_{max}$  is within a range of  $30-40^\circ$ , and wherein  $R_{D1}$  is at most 0.90, or within a range of 0.62 to 0.90.

7. The system of any one of claims 2-4, wherein  $\alpha_{max}$  is within a range of  $19-27^\circ$ , and wherein  $R_{D1}$  is at most 0.93, or within a range of 0.85 to 0.93.

8. The system of any one of claims 2-4, wherein  $\alpha_{\max}$  is within a range of 15-20°, and wherein  $R_{D1}$  is at most 0.97 or within a range of 0.90 to 0.97.
9. The system of any one of claims 1-8, wherein the controller is configured or programmed to calculate or select a ratio of the volume of formulation per unit of area of the two-dimensional projection of the target surface, before the microvalving;  
and wherein the controller is configured or programmed to control the microvalving such that a ratio of a volume of formulation applied per unit of area of a two-dimensional projection of the target surface, within any subdivision of said two-dimensional projection having an area of 5% or more of an area of the projection, is within  $\pm 10\%$  of said calculated or selected ratio.
10. The system of any one of claims 1-9, wherein said treatment station is further for increasing the surface energy of a top surface of said fully cured coating.
11. The system of any one of claims 2-10, wherein the system is devoid of dip coating and spin coating apparatus.
12. The system of any one of claims 1-11, wherein the system is not configured to perform the microvalving while causing relative rotational movement on a horizontal x-y plane between the microvalve apparatus and the target surface during the forming of the wet layer.
13. The system of claim 12, wherein the photochromic-ink-formulation-application station comprises a non-rotating optical-substrate holder.
14. A method of producing an optical construction on an optical substrate, the method comprising:
- (a) providing the system of any one of claims 1 to 13;
  - (b) microvalving drops of a liquid ink formulation onto an optical surface of the optical substrate, to form a wet layer, the liquid ink formulation containing a photochromic dye;  
and
  - (c) treating the wet layer to produce a dried or cured photochromic dye containing layer on the optical surface.
15. The method of claim 14, further comprising, prior to said microvalving, applying a primer to a first surface of the optical substrate to form a wet primer coating, and fully curing the wet primer coating to form the optical surface of the optical substrate.
16. The method of claim 15, wherein the cured primer coating has a non-tacky upper surface.
17. The method of claim 15 or 16, further comprising applying a surface energy treatment to the top surface of the fully-cured primer coating, prior to said microvalving.

18. The method of any one of claims 14 to 17, further comprising, after treating the wet layer to produce a dried dye-containing layer on the optical surface, applying a wet overcoat layer on top of the outer or exposed face of the dried photochromic dye containing layer.

19. The method of any one of claims 14 to 18, wherein said liquid ink formulation comprises

(a) a resin;

(b) a photochromic dye;

(c) a non-volatile liquid softening agent for softening the resin; and

(d) a solvent system including a very low vapor-pressure solvent **LLevap** and at least one of a high vapor-pressure solvent (**Hevap**) and a very high vapor-pressure solvent (**HHevap**);

wherein the resin, the photochromic dye, and the non-volatile liquid softening agent are dissolved within the solvent system, forming a single liquid phase;

wherein a first weight ratio (**WR1**) of the resin to the photochromic dye is at least 0.5:1;

wherein a second weight ratio (**WR2**) of the non-volatile liquid softening agent to the photochromic dye is at least 0.15:1;

wherein the non-volatile content of the ink formulation is within a range of 2.5 to 15%;

wherein a first solvent weight ratio (**SWR1**) of **Hevap**, **HHevap**, and **LLevap** to the total amount of solvent **Ts** within the ink formulation,

$$(\text{Hevap} + \text{HHevap} + \text{LLevap}) / \text{Ts}$$

is at least 0.7;

and wherein a relative solvent weight ratio (**RWSR**) of **LLevap** to a total **T<sub>H+HH</sub>** of **Hevap** and **HHevap**, is within a range of 0.15:1 to 2.2:1.

20. The method of claim 19, wherein **LLevap** has a relative evaporation rate **R<sub>LL</sub>** of at most 0.04.