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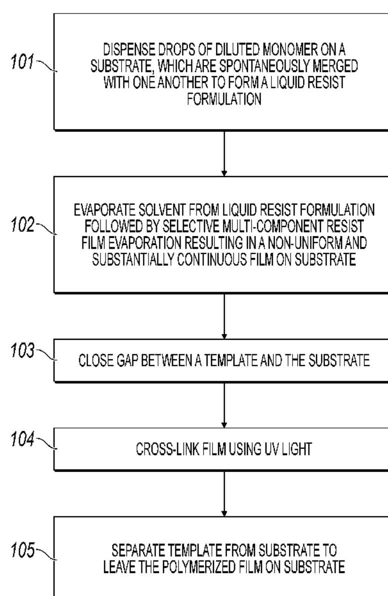

(57) **Abstract:** A method for fabricating patterns. An inverse optimization scheme is implemented to determine process parameters used to obtain a desired film thickness of a liquid resist formulation, where the liquid resist formulation includes a solvent and one or more non-solvent components. A substrate is covered with a substantially continuous film of the liquid resist formulation using one or more of the following techniques: dispensing discrete drops of a diluted monomer on the substrate using an inkjet and allowing the dispensed drops to spontaneously spread and merge, slot die coating and spin-coating. The liquid resist formulation is diluted in the solvent. The solvent is then substantially evaporated from the liquid resist formulation forming a film. A gap between a template and the substrate is then closed. The film is cured to polymerize the film and the substrate is separated from the template leaving the polymerized film on the substrate.

[Continued on next page]

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WAFER-SCALE PROGRAMMABLE FILMS FOR SEMICONDUCTOR PLANARIZATION AND FOR IMPRINT LITHOGRAPHY

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application Serial No. 62/370,259, entitled "Programmable Film Imprint Lithography," filed on August 3, 2016, which is incorporated by reference herein in its entirety.

GOVERNMENT INTERESTS

[0002] This invention was made with government support under Grant No. ECCS1120823 awarded by the National Science Foundation. The U.S. government has certain rights in the invention.

TECHNICAL FIELD

[0003] The present invention relates generally to nanoimprint lithography, and more particularly to developing wafer-scale programmable films for semiconductor planarization and for imprint lithography.

BACKGROUND

[0004] Nanoimprint lithography is a method of fabricating nanometer scale patterns that is low cost, high throughput and high resolution. It creates patterns by mechanical deformation of imprint resist and subsequent processes. The imprint resist is typically a monomer or polymer formulation that is cured by heat or UV light during the imprinting. Adhesion between the resist and the template is controlled to allow proper release.

[0005] There are many different variations of nanoimprint lithography. Among all the variants of nanoimprint lithography, Jet and Flash Imprint Lithography (J-FIL) offers distinct advantages in the replication of non-uniform patterns. This is because J-FIL uses drop-on-demand inkjetting as the preferred mode of material deposition, which allows pattern density based adaptive material placement.

[0006] The use of inkjetting as the preferred mode for material deposition leads to several challenges with respect to material formulation and dispensing. Apart from these, one of the most important problems that J-FIL needs to overcome is that of bubble trapping. This occurs

because of the use of discrete drops in the process, which are merged under the action of the template. This problem is circumvented by the use of an atmosphere of process gases, such as carbon dioxide or Helium or 1,1,1,3,3-pentafluoropropane (PFP); or the use of porous surfaces. However, for large-area printing formats, such as those typically processed in display glass configurations, it may be difficult to cover the entire substrate area, including the center, with the adequate amount of carbon dioxide or Helium before processing, to minimize bubble trapping.

[0007] Another problem arises in the printing of non-uniform pattern densities, where it becomes necessary to have non-uniform drop placement that matches with the pattern density variation.

SUMMARY

[0008] In one embodiment of the present invention, a method for fabricating patterns on rigid wafer substrates comprises implementing an inverse optimization scheme to determine process parameters used to obtain a desired film thickness of a liquid resist formulation, where the liquid resist formulation comprises a solvent and one or more non-solvent components. The method further comprises covering a substrate with a substantially continuous film of the liquid resist formulation using spin-coating, where the liquid resist formulation is diluted in the solvent. The method additionally comprises evaporating the solvent substantially from the liquid resist formulation forming a film. Furthermore, the method comprises closing a gap between a template and the substrate. Additionally, the method comprises curing the film to polymerize the film. In addition, the method comprises separating the substrate from the template leaving the polymerized film on the substrate.

[0009] In another embodiment of the present invention, a method for planarizing patterns on rigid wafer substrates comprises implementing an inverse optimization scheme with existing substrate topography as an input which is used to determine process parameters used to obtain a desired film thickness of a liquid resist formulation, where the liquid resist formulation comprises a solvent and one or more non-solvent components. The method further comprises covering a patterned substrate with a substantially continuous film of the liquid resist formulation using spin-coating, where the liquid resist formulation is diluted in the solvent. The method additionally comprises evaporating the solvent substantially from the liquid resist formulation forming a film. Furthermore, the method comprises curing the film to polymerize the film.

[0010] In a further embodiment of the present invention, a method for performing in-situ metrology comprises having an array of Atomic Force Microscope (AFM) tips with individually addressable locations. The method further comprises determining an optimum positioning of the array of AFM tips on a wafer with a pattern, a topography variation or a variation in a film thickness, wherein each AFM tip in the array of AFM tips provides data that is aggregated to infer the pattern, the topography variation or the film thickness variation. The method additionally comprises scanning the wafer to measure the pattern, the topography variation or the film thickness variation. Furthermore, the method comprises aggregating and analyzing the

measured pattern, the measured topography variation or the measured film thickness variation to infer the pattern, the topography variation or the film thickness variation.

[0011] The foregoing has outlined rather generally the features and technical advantages of one or more embodiments of the present invention in order that the detailed description of the present invention that follows may be better understood. Additional features and advantages of the present invention will be described hereinafter which may form the subject of the claims of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] A better understanding of the present invention can be obtained when the following detailed description is considered in conjunction with the following drawings, in which:

[0013] Figure 1 is a flowchart of a method of the inkjet-based P-FIL (IJ-PFIL) process for fabricating a pattern in accordance with an embodiment of the present invention;

[0014] Figures 2A-2F depict the cross-sectional views of fabricating a pattern using the steps described in Figure 1 in accordance with an embodiment of the present invention;

[0015] Figure 3 is a flowchart of method for fabricating replica templates and final substrates using roll-to-plate lithography in accordance with an embodiment of the present invention;

[0016] Figures 4A-4J depict the cross-sectional views of fabricating replica templates and final substrates using the steps described in Figure 3 in accordance with an embodiment of the present invention;

[0017] Figure 5 is a diagram of the framework for the inverse optimization scheme for IJ-PFIL in accordance with an embodiment of the present invention;

[0018] Figure 6 is a flowchart of a method of the spin-coated based P-FIL (SC-PFIL) process for fabricating a pattern in accordance with an embodiment of the present invention;

[0019] Figures 7A-7F depict the cross-sectional views of fabricating a pattern using the steps described in Figure 6 in accordance with an embodiment of the present invention;

[0020] Figure 8 is a flowchart of a method of an alternative embodiment of the spin-coated based P-FIL (SC-PFIL) process for fabricating a pattern in accordance with an embodiment of the present invention;

[0021] Figures 9A-9F depict the cross-sectional views of fabricating a pattern using the steps described in Figure 8 in accordance with an embodiment of the present invention;

[0022] Figure 10 is a diagram of the framework for the inverse optimization scheme for SC-PFIL in accordance with an embodiment of the present invention;

[0023] Figure 11 is a diagram of the framework for the inverse optimization scheme for Slot Die (SD)-PFIL in accordance with an embodiment of the present invention;

[0024] Figure 12 illustrates a stable bead formation in accordance with an embodiment of the present invention;

[0025] Figure 13 illustrates variation of film thicknesses with spin time and spin speed in accordance with an embodiment of the present invention;

[0026] Figure 14 is a flowchart of a method for fabricating nanoscale patterns made of high-index dielectric materials, such as TiO_2, on a flat surface in accordance with an embodiment of the present invention; and

[0027] Figures 15A-15D depict the cross-sectional views of fabricating nanoscale patterns on a flat surface using the steps described in Figure 14 in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION

[0028] As discussed herein, the principles of the present invention are directed to a novel process called Programmable Film Imprint Lithography (P-FIL). This process is compatible with various modes of material deposition, including inkjetting, slot die coating, and spin-coating, for coating a film of resist on rigid substrates. In one embodiment, the process may also be used in conjunction with film coating processes, such as dip coating on substrates that are not substantially flat. The thickness of the resist film, just before the patterning step, is substantially continuous and may be non-uniform depending on the given pattern density variations. This non-uniformity may be (i) substantially correlated with an initial non-uniform material distribution or, (ii) can be enhanced from an initial uniform distribution of material through controlled external inputs, such as distributed thermal actuation or controlled gas flow, to evaporate the resist film with spatial selectivity or, (iii) a combination of approaches (i) and (ii). In addition, distributed inkjetting of material can be used to add more material selectively on top of films that are deposited using spin coating and slot die coating, etc. This may be necessitated in cases where simultaneous patterning of micro- and nano-scale structures is desired. In this case, the thickness of the deposited film may be made compatible with the nano-scale structures, while inkjetting of larger drops may be used to cater to the micro-scale structures. The achievement of a programmed non-uniform and substantially continuous film is driven by an optimization program that informs the initial material distribution and the nature of external inputs, such as evaporation or gas flow.

[0029] In one embodiment, after achieving the desired non-uniform and substantially continuous film on a substrate, the gap between the resist-coated substrate and a patterned template is closed to fill the template pattern. The resist film is then cross-linked using UV light and the template is then separated from the substrate to leave the polymerized resist film on the substrate.

[0030] In another embodiment, an intentionally non-uniform film is formed on a pre-patterned substrate or an un-patterned substrate using the methods described in the previous paragraph. This is done to compensate for substrate topography variations to achieve a desired final substrate topography. Exemplar desired final substrate topography may be one of the following: (i) flat or substantially flat as in the field of wafer polishing or fabrication of optical flats, or (ii) locally flat (over micrometer or millimeter length scales) while globally (over tens of millimeters

or more) conforming to the incoming substrate topography as in the field of semiconductor planarization. In one embodiment, a goal of the process of the present invention is to deposit an intentionally non-uniform film on a substrate where the resulting top surface has no patterns. Hence, the liquid resist material may be cross-linked in the free surface state or contact may be made against a superstrate that is substantially free from nanoscale and microscale patterns. In the free surface state, exemplar materials can include the use of low-viscosity materials, such as the one developed for reverse-tone step and flash imprint lithography, such as discussed in Lin, M.W., "Simulation and design of planarizing materials and interfacial adhesion studies for step and flash imprint lithography," Ph.D. Dissertation, The University of Texas at Austin, 2008, which is incorporated by reference herein in its entirety. By covering the top of the liquid film, the superstrate influences the evolution dynamics of the thin film. Its geometry can thus be optimized, by locally changing its thickness, to match the desired substrate topography and process specifications.

[0031] As discussed below, selected embodiments of the PFIL process are described with different material deposition methods, where the patterned template results in a pattern on the top of the deposited material.

[0032] While the following discusses the present invention in the context of inkjet printing, spin-coating and slot die coating, the principles of the present invention may be practiced using other coating methods as well. A person of ordinary skill in the art would be capable of applying the principles of the present invention to such implementations. Further, embodiments applying the principles of the present invention to such implementations would fall within the scope of the present invention.

[0033] As discussed in the Background section, one of the most important problems that J-FIL needs to overcome is that of bubble trapping. The aforementioned problem of bubble trapping with inkjets can be overcome if larger drops, that are spaced closer together, are used. Such drops may not need the action of the template to merge and form a contiguous film. They may be able to merge spontaneously and form a film that can then be imprinted on. However, the use of larger resist volume corresponds to thicker residual layers which may be undesirable when the resist pattern needs to be transferred to the underlying films via dry etching or wet etching processes. Moreover, thicker residual layers can lead to problems in residual layer thickness

uniformity control which can also lead to sub-optimal pattern transfer after etching. Thus, there is an inherent conflict between the use of higher volume for drop merging and lower volume needed for good etching performance.

[0034] One way in which this problem can be overcome is through the use of resist drops that are diluted by solvents. Details of material design are discussed further below. This increases their volume without increasing the monomer content and can thus lead to favorable drop spreading and merging characteristics without using the template to force the formation of a contiguous film in an ambient environment that may not need process gases, such as carbon dioxide, Helium or PFP discussed earlier.

[0035] The solvent concentration in the resist formulation cannot be increased arbitrarily, as that might compromise the rheological properties of the resist solution. Also, drops of highly diluted solutions can form fingering instabilities at the edges because of preferential evaporation from the periphery of the drops. Hence, it is important to constrain the material design to prevent the solvent from evaporating substantially in the drop dispensing, spreading and merging stages, as that might compromise with the control of the resist residual layer thickness distribution. Rather, the solvent should be substantially evaporated immediately after merging of the drops to form a continuous film. This would lead to a film with only the desired resist material and with low thickness that may not want to redistribute as much. A flowchart of the inkjet-based P-FIL (IJ-PFIL) process that overcomes the bubble trapping with inkjets is discussed below in connection with Figure 1.

[0036] Figure 1 is a flowchart of a method 100 of the inkjet-based P-FIL (IJ-PFIL) process for fabricating a pattern in accordance with an embodiment of the present invention. Figures 2A-2F depict the cross-sectional views of fabricating a pattern using the steps described in Figure 1 in accordance with an embodiment of the present invention.

[0037] Referring now to Figure 1, in conjunction with Figures 2A-2F, in step 101, drops of a diluted monomer 201 (diluted in a solvent) are dispensed on a substrate 202 as shown in Figure 2A, which are spontaneously merged with one another as shown in Figure 2B, forming a liquid resist formulation 203 (containing the solvent and one or more non-solvent components, such as the monomer) as shown in Figure 2C. In one embodiment, the inkjet is used to dispense discrete drops of diluted monomer which does not form a substantially continuous film to locally modify

film thickness profiles prior to closing the gap between template 205 and substrate 202 (discussed below).

[0038] In one embodiment, the inkjet drop dispense and spontaneous drop merging stages can be done at a tool location where the temperature and air flow are highly controlled and kept intentionally low to minimize evaporation. This would be beneficial for inkjet drop dispensing as the material formulation would be more stable. Evaporation of material from the drop as it is in-flight or sitting on substrate 202 before and during merging is not desirable. As soon as the drops have merged to form a contiguous film, the processing can then be transferred to a tool location where the temperature is at a higher mean value than the location where drop merging happens. This higher mean temperature can take place through a heated substrate and or chuck, for example, and should make the solvent volatile while also favorably changing the surface tension and viscosity of the solution. It is also important to note here that the entire solvent volume needs to be evaporated, to prevent recondensation of the solvent on the substrate. Any remaining solvent can lead to voids or cracks in the cured resist, which is highly undesirable.

[0039] As a result, in step 102, solvent is evaporated (e.g., blanket evaporation) from liquid resist formulation 203 followed by selective multi-component resist film evaporation resulting in a non-uniform and substantially continuous film 204 on substrate 202 as shown in Figure 2D. In one embodiment, the liquid resist formulation consists of solvent with a substantially higher volatility than the rest of the components of the liquid resist formulation. In one embodiment, the non-solvent component(s) of the liquid resist formulation have substantially similar volatility. In one embodiment, the non-solvent component(s) of the liquid resist formulation except for a photoinitiator have a boiling point that differ by less than 30° C, 10° C or 5° C. In one embodiment, the non-solvent component(s) include a thermoset polymer with a high glass transition temperature. In one embodiment, the non-solvent component(s) include silicon or carbon.

[0040] In one embodiment, as discussed herein, an inverse optimization scheme may be used to determine process parameters used to obtain a desired film thickness of the liquid resist formulation. In one embodiment, the inverse optimization scheme includes one or more of the following: genetic algorithms, simulated annealing, and full pattern search to achieve an objective function of minimizing an error between a function of the desired film thickness and

the obtained film thickness. In one embodiment, a forward model is used as a core for the inverse optimization scheme to predict a film thickness profile, where the forward model incorporates one or more of the following: thermal transport, solute transport, and solvent transport. In one embodiment, the liquid resist formulation, whose solvent has already been evaporated, is selectively evaporated to form film 204 with an intentionally non-uniform profile to match a desired thickness profile. In one embodiment, the selective evaporation is carried out by one or more of the following: a temperature controlled substrate chuck, an array of individually controllable infrared lamps, an array of individually controllable fans to control air flow, individually controllable micro heaters or coolers on substrate 202, and a spatial light modulator (may include one or more Digital Micromirror Device (DMD) arrays) to control one or more sources of electromagnetic radiation. In one embodiment, the solvent evaporation, selective resist evaporation and imprinting are carried out in stations that may be separated by barriers that prevent vapor transport between the stations. In one embodiment, the selective evaporation is carried out in an environment with controlled vapor pressures. In one embodiment, there is a stack of film(s) used between the liquid resist formulation and substrate 202 that substantially absorbs electromagnetic radiation.

[0041] In one embodiment, after solvent evaporation, the control of resist film evaporation can be done in a separate station, which is physically separated with barriers, through judicious control of temperature through a distributed set of thermal actuators, infrared (IR) lamps, or combinations thereof, in which each element in the set can be individually controlled. This individual control in infra-red (IR) lamps, for example, can be achieved through devices, such as Digital Micromirror Device (DMD) Arrays from Texas Instruments. A state-of-the-art array has 4M pixels at a pitch of 7.6 micrometers at a diagonal width of 0.9 inches. This can enable spatial modulation of IR intensity to control the evaporation over at least an area of ~ 0.4 sq. inch. With the appropriate reduction optics, a larger area can be projected upon, but by compromising resolution. As an example, a resist formulation containing methyl methacrylate (MMA) as the liquid monomer and primary component, would need a local heat source of ~ 1 W to absorb sufficient heat at normal temperature and pressure to evaporate ~100 nm of liquid film from a local 50 x 50 μm^2 area, assuming the starting film thickness is 500 nm. Such powers can be delivered using DMD arrays. These devices also have frame rates approaching 10 kHz, and

thereby provide high frequency temporal control of the incident radiation and subsequent evaporation.

[0042] Additionally, multiple DMD arrays can be used across a larger area, if resolution cannot be compromised further. The individual pixels may have significant cross-talk, which can also be modeled and incorporated in the forward model for thin film evaporation. Additionally, an underlying substrate with MEMS-based micro-heaters may also be used for enhanced temperature distribution, if a higher resolution is required than what can be afforded by the DMD arrays. This principle of selective heating can be generally applied to all embodiments of the present invention and is not specific to only IJ-PFIL.

[0043] After selective heating and achievement of the desired resist film thickness, a gap between template 205 and substrate 202 is then closed (bringing corresponding template 205 in contact with film 204) in step 103 as shown in Figure 2D. In one embodiment, template 205 is patterned with a lateral feature dimension of less than 500 nm. In one embodiment, template 205 is patterned with a lateral feature dimension of less than 100 nm. In one embodiment, the template consists of a three-dimensional shape or a multi-tiered pattern as discussed in P. Joseph et al., "Fabrication of self-aligned multilevel nanostructures," Microelectronic Engineering, 169(5), 2017 and in Praveen Joseph, "Self-Aligned Integrated Nanostructures Fabricated by UV-Nanoimprint Lithography," Ph.D. Dissertation, The University of Texas at Austin, 2017, which are incorporated by reference herein in their entirety. In one embodiment, contact between the substrate and the template is initiated substantially along a line or substantially at a point. This is done to prevent substantial area contact, as it can potentially lead to trapping of bubbles and voids because of the flexible nature of the substrate. In one embodiment, precise motion control and/or force control is employed while closing the gap to prevent impact between the template and the substrate. Impact and high contact pressures can lead to distortion of nanoscale features. Moreover, the exact location of the substrate plane is not known with high precision when the substrate is held in a roll-to-roll configuration under tension. This uncertainty in the location of the substrate plane requires precise detection of contact through accurate calibration of forces, which can be done through force sensors. In one embodiment, substantial line or point contact is enabled by either keeping the surface of the substrate and the template convex, or by having one surface concave and the other convex with a higher radius of curvature. In one embodiment, contact between the template and roll-to-roll substrate is enabled along a line where the substrate

is supported by an idle roller or on a chuck with substantially low friction. Materials, such as Diamond-like Carbon (DLC), can be used for this purpose as they are effective solid-phase lubricants. Substantial contact of the substrate against the roller or a chuck can be enabled by keeping the remaining roll-to-roll substrate path at a level lower than the roller or chuck. In one embodiment, the chuck is an air cavity chuck as discussed in U.S. Patent Nos. 6,982,783; 7,019,819 and 6,980,282, which are incorporated by reference herein in their entirety.

[0044] In step 104, film 204 is then cross-linked using UV light 206 as shown in Figure 2E. That is, film 204 is cured by cross-linking so as to polymerize film 204.

[0045] In step 105, template 205 is separated from substrate 202 to leave the polymerized film 207 on substrate 202 as shown in Figure 2F.

[0046] In one embodiment, template 205 has a multi-tiered pattern and/or a three-dimensional shape. In one embodiment, template 205 is flexible or held in a roll-to-roll configuration. This template configuration can be realized after substrate 202 is patterned using a rigid template 205, and can be used to pattern large-area substrates, such as glass panels, as discussed in U.S. Patent No. 9,616,614, which is incorporated by reference herein in its entirety. In general, a roll-to-roll PFIL approach can support both roll-to-roll and roll-to-plate (R2P) lithography. The former involves having both the template and the substrate held in roll-to-roll configurations, while the latter has one of the two held in a roll-to-roll configuration with the other being a rigid substrate, such as a wafer or a glass panel. In one embodiment, the substrate is assumed to be held in a roll-to-roll configuration while the template is rigid. An example of roll-to-plate lithography to make replica templates, and final substrates, is provided in Figures 3 and 4A-4J. Figure 3 is a flowchart of method 300 for fabricating replica templates and final substrates using roll-to-plate lithography in accordance with an embodiment of the present invention. Figures 4A-4J depict the cross-sectional views of fabricating replica templates and final substrates using the steps described in Figure 3 in accordance with an embodiment of the present invention.

[0047] Referring to Figure 3, in conjunction with Figures 4A-4I, in step 301, a master template 401 is fabricated, such as using e-beam, photolithography, etc., as shown in Figure 4A.

[0048] In step 302, master template 401 is slot-die coated with resist 402 as shown in Figure 4B.

[0049] In step 303, imprint on resist 402 using roll-to-plate (R2P) lithography (imprint rollers 403, plate 404) and cure forming replica 405 as shown in Figures 4C and 4D.

[0050] In step 304, replica 405 is separated from master template 401 as shown in Figure 4D and the process is repeated (steps 302-304) to fabricate further replicas 405.

[0051] In step 305, oxide 406 is deposited on master template 401 as shown in Figure 4E.

[0052] In step 306, replica 405 is imprinted (R2P) on master template 401 with oxide 406 forming replica template 407 as shown in Figures 4E and 4F.

[0053] Step 306 is repeated to fabricate a roll of replica templates 407 with a protective interleaf as shown in Figure 4F.

[0054] In step 307, a substrate 408 is slot-die coated with resist 409 as shown in Figure 4G.

[0055] In step 308, resist 409 is imprinted (R2P) using replica template 407 and cured as shown in Figure 4H.

[0056] In step 309, substrate 408 is separated from replica template 407 forming a patterned resist 410 on substrate 408 as shown in Figures 4I and 4J.

[0057] While such a method can potentially overcome problems with bubble trapping, it can be further enhanced by the use of an inverse model to also address varying template pattern geometry to determine optimum drop locations and volumes. The inverse model may also include parameters of the Digital Micromirror Device (DMD) array, for example, the spatial distribution and frequency of switching of individual mirrors, to control the spatial evaporation profile. In one embodiment, the inverse optimization scheme may be augmented to determine one of the following: a spatial evaporation profile, a spatial temperature profile, a spatial material removal profile, a spatial evaporation rate profile, and a spatial material removal rate profile.

[0058] In one embodiment, the inverse model should be wrapped around a forward model that takes into account thin film flow in the presence of evaporation and surface tension driven gradients for the drop spreading, merging and evaporation stages prior to imprinting. A framework for this optimization scheme is shown in Figure 5. Figure 5 is a diagram of the framework for the inverse optimization scheme for IJ-PFIL in accordance with an embodiment of the present invention.

[0059] Referring to Figure 5, optimization solver 501 receives as inputs, the process parameters 502, topography 503, a desired pre-imprint residual layer thickness (RLT) profile 504, which uses the template pattern 505 as an input, and a predicted pre-imprint RLT profile 506.

[0060] Optimization solver 501 outputs the inkjet material distribution 507, temperature distribution 508 and merging and spreading times 509. The initial volumes and locations 510, which receives as input, the inkjet material distribution 507, as well as temperature distribution 508 and merging and spreading times 509 are inputs to the thin film and evaporation model 511 which is inputted to predicted pre-imprint RLT profile 506.

[0061] Furthermore, template pattern 505 is inputted to heuristics 512 which is inputted to initial volumes and locations 510.

[0062] In one embodiment, such an inverse optimization scheme is implemented by a computing system.

[0063] It is noted that any deviations in drop volume in the drop dispense stage can be overcome through image-processing based drop volume and velocity control. The inverse model for determining optimum drop volumes and locations can also leverage prior work from Sreenivasan et al. (U.S. Patent Application Publication No. 2015/0048050), which is incorporated by reference herein in its entirety. Ideally, the boiling point of the solvent should be much lower than the rest of the resist components, such that there is minimal evaporation of the resist when evaporating the solvent. For example, the boiling point of the XNIL-26SF resist from MicroResist Technologies is close to 180° C, whereas, the boiling point of a common solvent, such as PGMEA, is close to 140° C. This selective evaporation of the resist material can enable a desired film thickness profile, based on the need to obtain a uniform residual layer in the presence of non-uniform patterns, or address substantially systematic process parasitics, such as non-uniform shrinkage upon cross-linking and non-uniform etch rates in etch tools. The film thickness profile can also be used to obtain a desired functional performance, such as desired optical performance, mechanical stability, etc. When a resist is partially evaporated in this manner, it is desirable that the relative evaporation rates of all the components of the resist are substantially the same to ensure the resist remains consistent in its properties. This can be done by keeping the boiling points of the components of the resist mixture within a range of 10° C

with each other. For substrate planarization, however, the material design may involve additional considerations. Details of material design are discussed further below.

[0064] In one embodiment of the P-FIL process, spin-coating is the preferred material deposition technique. Spin-coating, followed by baking, is a commonly used technique for obtaining substantially uniform films on rigid substrates. The challenge with spin-coating is its inability to cater to non-uniform material requirement in the presence of template pattern variation, which can be overcome using SC-PFIL. An embodiment of the process flow for SC-PFIL is shown in Figure 6.

[0065] Figure 6 is a flowchart of a method 600 of the spin-coated based P-FIL (SC-PFIL) process for fabricating a pattern in accordance with an embodiment of the present invention. Figure 6 will be discussed below in connection with Figures 7A-7F. Figures 7A-7F depict the cross-sectional views of fabricating a pattern using the steps described in Figure 6 in accordance with an embodiment of the present invention.

[0066] Referring now to Figure 6, in conjunction with Figures 7A-7F, in step 601, an initial volume of diluted monomer 701 (diluted in a solvent) is deposited on substrate 702 forming a liquid resist formulation as shown in Figure 7A.

[0067] In step 602, solvent 703 is evaporated from the liquid resist formulation during spin-coating and baking forming a thin film of monomer 704 with little or no concentration of solvent as shown in Figures 7B and 7C. In one embodiment, there is a stack of film(s) used between the liquid resist formulation and substrate 702 that substantially absorbs electromagnetic radiation. In one embodiment, the liquid resist formulation consists of solvent with a substantially higher volatility than the rest of the components of the liquid resist formulation. In one embodiment, the non-solvent component(s) of the liquid resist formulation have substantially similar volatility. In one embodiment, the non-solvent component(s) of the liquid resist formulation except for a photoinitiator have a boiling point that differ by less than 30° C, 10° C or 5° C. In one embodiment, the non-solvent component(s) include a thermoset polymer with a high glass transition temperature. In one embodiment, the non-solvent component(s) include silicon or carbon.

[0068] In step 603, the thin film of monomer 704 is selectively evaporated, such as via infra-red (IR) lamps, forming a non-uniform and substantially continuous film 705 on substrate 702 as

shown in Figure 7D. In one embodiment, the selective evaporation is carried out by one or more of the following: a temperature controlled substrate chuck, an array of individually controllable infrared lamps, an array of individually controllable fans to control air flow, individually controllable micro heaters or coolers on substrate 702, and a spatial light modulator (may include one or more Digital Micromirror Device (DMD) arrays) to control one or more sources of electromagnetic radiation. In one embodiment, the solvent evaporation, selective resist evaporation and imprinting are carried out in stations that may be separated by barriers that prevent vapor transport between the stations. In one embodiment, the selective evaporation is carried out in an environment with controlled vapor pressures. In one embodiment, the liquid resist formulation, whose solvent has already been evaporated, which consists of the monomer film 704, is selectively evaporated to form film 705 with an intentionally non-uniform profile to match a desired thickness profile.

[0069] In step 604, a gap between a template 706 and substrate 702 is then closed (bringing template 706 down in contact with film 705) as shown in Figure 7D. In one embodiment, template 706 is patterned with a lateral feature dimension of less than 500 nm. In one embodiment, template 706 is patterned with a lateral feature dimension of less than 100 nm.

[0070] In step 605, film 705 is then cross-linked using UV light 707 as shown in Figure 7E. That is, film 705 is cured by cross-linking so as to polymerize film 705.

[0071] In step 607, template 706 is separated from substrate 702 to leave the polymerized film 708 on substrate 702 as shown in Figure 7F.

[0072] An alternative embodiment of the process flow for SC-PFIL is discussed below in connection with Figures 8 and 9A-9F.

[0073] Figure 8 is a flowchart of a method 800 of an alternative embodiment of the spin-coated based P-FIL (SC-PFIL) process for fabricating a pattern in accordance with an embodiment of the present invention. Figure 8 will be discussed below in connection with Figures 9A-9F. Figures 9A-9F depict the cross-sectional views of fabricating a pattern using the steps described in Figure 8 in accordance with an embodiment of the present invention.

[0074] Referring now to Figure 8, in conjunction with Figures 9A-9F, in step 801, an initial volume of diluted monomer 901 (diluted in a solvent) is deposited on substrate 902 forming a liquid resist formulation as shown in Figure 9A.

[0075] In step 802, solvent 903 is evaporated form the liquid resist formulation during spin-coating and baking forming a thin film of monomer 904 with little or no concentration of solvent as shown in Figures 9B and 9C. In one embodiment, there is a stack of film(s) used between the liquid resist formulation and substrate 902 that substantially absorbs electromagnetic radiation. In one embodiment, the liquid resist formulation consists of solvent with a substantially higher volatility than the rest of the components of the liquid resist formulation. In one embodiment, the non-solvent component(s) of the liquid resist formulation have substantially similar volatility. In one embodiment, the non-solvent component(s) of the liquid resist formulation except for a photoinitiator have a boiling point that differ by less than 30° C, 10° C or 5° C. In one embodiment, the non-solvent component(s) include a thermoset polymer with a high glass transition temperature. In one embodiment, the non-solvent component(s) include silicon or carbon.

[0076] In step 803, the thin film of monomer 904 is selectively evaporated, such as via infra-red (IR) lamps, forming a non-uniform and substantially continuous film 905 on substrate 902 as shown in Figure 9D. In one embodiment, the selective evaporation is carried out by one or more of the following: a temperature controlled substrate chuck, an array of individually controllable infrared lamps, an array of individually controllable fans to control air flow, individually controllable micro heaters or coolers on substrate 902, and a spatial light modulator (may include one or more Digital Micromirror Device (DMD) arrays) to control one or more sources of electromagnetic radiation. In one embodiment, the selective evaporation and patterning are carried out in separate stations to avoid recondensation of evaporated materials onto substrate 902 prior to patterning. In one embodiment, the selective evaporation is carried out in an environment with controlled vapor pressures. In one embodiment, the liquid resist formulation, whose solvent has already been evaporated, which consists of the monomer film 904, is selectively evaporated to form film 905 with an intentionally non-uniform profile to match a desired thickness profile.

[0077] In step 804, a gap between a superstrate 906 and substrate 902 is then closed (bringing superstrate 906 down in contact with film 905) as shown in Figure 9D. In one embodiment, superstrate 906 is used to cover the top of film 905 to obtain desired evolution dynamics of film 905. In one embodiment, a superstrate thickness profile of superstrate 906 and geometry are optimized to obtain desired evolution dynamics for a given substrate topography. In one embodiment, superstrate 906 is flexible or held in a roll-to-roll configuration.

[0078] In step 805, film 905 is then cross-linked using UV light 907 as shown in Figure 9E. That is, film 905 is cured by cross-linking so as to polymerize film 905.

[0079] In step 806, superstrate 906 is separated from substrate 902 to leave the polymerized film 908 on substrate 902 as shown in Figure 9F.

[0080] Like IJ-PFIL, here, too, the material can be substantially diluted using solvents, although the process can be executed using resist materials that are substantially free of solvents. Details of material design are discussed further below. Thus, the monomer resist material concentration can be minimized to reduce the waste of expensive material. During execution of the spin-coating and subsequent baking process, almost all of the solvent 703, 903 evaporates leading to a thin film of monomer resist 704, 904 with little or no concentration of solvent. This evaporation during the spin-coating process can also be affected by the air flow in the vicinity. Unlike IJ-PFIL, where the initial material distribution can be controlled to get an initially non-uniform film, in SC-PFIL, the coated film immediately after spin-coating is typically substantially uniform. There is, however, a minimum initial volume of material that is dispensed to obtain the desired film thickness, regardless of uniformity. This film thickness also depends on spin speed and total process time. Thus, the inverse model can be used to obtain optimum values for these parameters to obtain an initial uniform thick film (e.g., thickness of liquid resist formulation) that can then be driven to non-uniformity using controlled evaporation of the monomer in a physically separated station, similar to IJ-PFIL.

[0081] As the solvent is substantially evaporated in the spin-coating step, the model can be augmented to account for evaporation of the resist which drives the final film thickness profile. At the same time, it should be ensured that the evaporating solvent is completely evaporated and exhausted before the substrate is carried to the patterning station, to prevent recondensation of the solvent on the substrate. Any residual solvent, either on the substrate or in the vapor phase,

can create problems with voids, feature collapse or parasitic condensation on the patterned resist. A framework for inverse optimization in the SC-PFIL process is shown in Figure 10.

[0082] Figure 10 is a diagram of the framework for the inverse optimization scheme for SC-PFIL in accordance with an embodiment of the present invention.

[0083] Referring to Figure 10, optimization solver 1001 receives as inputs, the input parameters 1002, topography 1003, a desired pre-imprint residual layer thickness (RLT) profile 1004, which uses the template pattern 1005 as an input, and a predicted pre-imprint RLT profile 1006.

[0084] Optimization solver 1001 outputs the initial volume of material 1007, temperature distribution 1008 and spin process parameters 1009. The film thickness after spin-coating 1010, which receives as input, the initial volume of material 1007, as well as temperature distribution 1008 and merging and spin process parameters 1009 are inputs to the thin film and evaporation model 1011 which is inputted to predicted pre-imprint RLT profile 1006.

[0085] Furthermore, template pattern 1005 is inputted to heuristics 1012 which is inputted to film thickness after spin-coating 1010.

[0086] In one embodiment, such an inverse optimization scheme is implemented by a computing system.

[0087] The control of resist evaporation can be done through judicious control of temperature through a distributed set of thermal actuators, IR lamps, or combinations thereof, in which each element in the set can be individually controlled. This individual control in IR lamps, for example, can be achieved through devices, such as Digital Micromirror Device (DMD) Arrays from Texas Instruments. A state-of-the-art array has 4M pixels at a pitch of 7.6 micrometers at a diagonal width of 0.9 inches. This can enable spatial modulation of IR intensity to control the evaporation over at least an area of ~ 0.4 sq. inch. With the appropriate reduction optics, a larger area can be projected upon, but by compromising resolution. As an example, a resist formulation containing methyl methacrylate (MMA) as the liquid monomer and primary component, would need a local heat source of ~ 1 W to absorb sufficient heat at normal temperature and pressure to evaporate ~100 nm of liquid film from a local 50 x 50 μm^2 area, assuming the starting film thickness is 500 nm. Such powers can be delivered using DMD arrays. These devices also have frame rates approaching 10 kHz, and thereby provide high frequency temporal control of the

incident radiation and subsequent evaporation. The inverse model may also include parameters of the DMD array, for example, the spatial distribution and frequency of switching of individual mirrors, to control the spatial evaporation profile.

[0088] Additionally, multiple DMD arrays can be used across a larger area, if resolution cannot be compromised further. The individual pixels may have significant cross-talk, which can also be modeled and incorporated in the forward model for thin film evaporation. Additionally, an underlying substrate with MEMS-based micro-heaters may also be used for enhanced temperature distribution, if a higher resolution is required than what can be afforded by the DMD arrays. This principle of selective heating can be generally applied to all embodiments of the present invention and is not specific to only SC-PFIL. As mentioned earlier, the starting material can be substantially free from the solvent and may only consist of the monomer resist (e.g., XNIL26-SF resist from MicroResist Technologies). Regardless of the initial material composition, the approach presented herein uses controlled resist evaporation thereby removing a portion of the monomer mixture that is to be cross-linked. This selective evaporation of the resist material can enable a desired film thickness profile, based on the need to obtain a uniform residual layer in the presence of non-uniform patterns, or address substantially systematic process parasitics, such as non-uniform shrinkage upon cross-linking, and non-uniform etch rates in etch tools. The film thickness profile can also be used to obtain a desired functional performance, such as desired optical performance, mechanical stability, etc. When a resist solution is partially evaporated in this manner, it is desirable that the relative boiling points of all the components of the resist are substantially the same, for example, within 10° C of each other, to ensure the resist mixture remains consistent in its properties; and it is desirable to not include a solid material as a component of the resist mixture. For substrate planarization, however, the material design may involve additional considerations. Details of material design are discussed further below.

[0089] In this embodiment of the P-FIL process (slot die coating based P-FIL (SD-PFIL)), slot die coating is the material deposition technique. Slot die coating is an inexpensive process that has been used traditionally for coating rectangular substrates, such as display glass. The challenge with slot die coating is that it is extremely difficult to obtain nanoscale wet films of the thickness desired for nanoscale imprint lithography process residual layer films that have a mean thickness of less than 50 nm.

[0090] Like IJ-PFIL, here, too, the material can be substantially diluted using solvents. Details of material design are discussed further below. Thus, the resist material concentration can be minimized to reduce the waste of expensive material. During execution of the slot die coating process and baking step, almost all of the solvent evaporates leading to a thin film of monomer resist with little or no concentration of solvent. This evaporation during the slot die coating process can also be affected by the air flow in the vicinity. Unlike IJ-PFIL, where the initial material distribution can be controlled to get an initially non-uniform film, in SD-PFIL, the coated film immediately after slot die coating is substantially uniform in at least one dimension. However, regardless of uniformity, there is a combination of process parameters that leads to a desired mean film thickness (e.g., desired thickness of liquid resist formulation) after slot die coating. Other than the material rheology, these control parameters include speed of the substrate relative to the die and coating gap. Thus, the inverse model can be used to obtain optimum values for these parameters to obtain an initial uniform thick film that can then be driven to non-uniformity using controlled evaporation of the remaining resist in a separate station. Moreover, the relation between these parameters and the film thickness can be quite complex to model. This is because the relation depends on the “region of operation” of the slot die coater. Typically, it would be preferred to have the coater operate in the so-called “region III,” where the wet film thickness decreases with increasing speed, leading to favorable throughput. However, there might be situations where the material rheology may constrain the operation to only outside this region. Hence, the inverse model may be augmented with heuristics to determine an optimum set of values.

[0091] At the same time, it should be ensured that the evaporating solvent is completely evaporated and exhausted before the substrate is carried to the patterning station. Any residual solvent, either on the substrate or in the vapor phase, can create problems with voids, feature collapse or parasitic condensation on the patterned resist. A framework for inverse optimization in the SD-FIL process is shown in Figure 11.

[0092] Figure 11 is a diagram of the framework for the inverse optimization scheme for SD-PFIL in accordance with an embodiment of the present invention.

[0093] Referring to Figure 11, optimization solver 1101 receives as inputs, the input parameters 1102, topography 1103, a desired pre-imprint residual layer thickness (RLT) profile 1104, which uses the template pattern 1105 as an input, and a predicted pre-imprint RLT profile 1106.

[0094] Optimization solver 1101 outputs the region of operation 1107, temperature distribution 1108 and slot die process parameters 1109. The film thickness after slot die coating 1110, which receives as input, the region of operation 1107, as well as temperature distribution 1108 and slot die process parameters 1109 are inputs to the thin film and evaporation model 1111 which is inputted to predicted pre-imprint RLT profile 1106.

[0095] Furthermore, template pattern 1105 is inputted to heuristics 1112 which is inputted to film thickness after slot die coating 1110.

[0096] In one embodiment, such an inverse optimization scheme is implemented by a computing system.

[0097] The control of resist evaporation can be done through judicious control of temperature through a distributed set of thermal actuators, IR lamps, or combinations thereof, in which each element in the set can be individually controlled. This individual control in IR lamps, for example, can be achieved through devices, such as Digital Micromirror Device (DMD) Arrays from Texas Instruments. A state-of-the-art array has 4M pixels at a pitch of 7.6 micrometers at a diagonal width of 0.9 inches. This can enable spatial modulation of IR intensity to control the evaporation over at least an area of ~ 0.4 sq. inch. With the appropriate reduction optics, a larger area can be projected upon, but by compromising resolution. As an example, a resist formulation containing methyl methacrylate (MMA) as the liquid monomer and primary component, would need a local heat source of ~ 1 W to absorb sufficient heat at normal temperature and pressure to evaporate ~100 nm of liquid film from a local 50 x 50 μm^2 area, assuming the starting film thickness is 500 nm. Such powers can be delivered using DMD arrays. These devices also have frame rates approaching 10 kHz, and thereby provide high frequency temporal control of the incident radiation and subsequent evaporation. The inverse model may also include parameters of the DMD array, for example, the spatial distribution and frequency of switching of individual mirrors, to control the spatial evaporation profile.

[0098] Additionally, multiple DMD arrays can be used across a larger area, if resolution cannot be compromised further. Compensation of any process parasitics resulting from sequential

processing under different DMD arrays can be incorporated in the inverse optimization framework. In one embodiment, the inverse optimization framework compensates for sequentially selective evaporation from one or more DMD arrays, or temperature profiles resulting from heat capacity of the substrate or material, or deterministic changes in film thickness profile due to known changes in ambient conditions or when handling or transporting the substrate. In one embodiment, the individual pixels may also have significant cross-talk, which can also be modeled and incorporated in the forward model for thin film evaporation. Additionally, an underlying substrate with MEMS-based micro-heaters may also be used for enhanced temperature distribution, if a higher resolution is required than what can be afforded by the DMD arrays. In one embodiment, the starting material can be substantially free from the solvent and may only consist of the resist (e.g., XNIL26-SF resist from MicroResist Technologies). The approach presented herein uses controlled resist evaporation thereby removing a portion of the monomer mixture that is to be cross-linked. This selective evaporation of the resist material can enable a desired film thickness profile, based on the need to obtain a uniform residual layer in the presence of non-uniform patterns, or address substantially systematic process parasitics, such as non-uniform shrinkage upon cross-linking, and non-uniform etch rates in etch tools. The film thickness profile can also be used to obtain a desired functional performance, such as desired optical performance, mechanical stability, etc. When a resist mixture is partially evaporated in this manner, it is desirable that the relative boiling points of all the components of the resist are substantially the same, for example, within 10° C of each other, to ensure the resist mixture remains consistent in its properties; and it is desirable to not include a solid monomer material as a component of the monomer mixture. For substrate planarization, however, the material design may involve additional considerations. Details of material design are discussed further below.

[0099] Concerning modeling, a general forward model is now discussed. Flow of a fluid in domains that have much smaller thickness than lateral length scales are adequately described by the lubrication approximation. For Marangoni, i.e., surface tension gradient, driven flows in the presence of evaporation, the lubrication approximation leads to the following equation:

$$\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}\left\{\frac{h^3}{3\mu}\left[\gamma\frac{\partial^3 h}{\partial x^3}+\frac{\partial}{\partial x}\left(\frac{J^2}{\rho_v}\right)\right]+\frac{h^2}{2\mu}\frac{\partial\gamma}{\partial x}\right\}=-\frac{J}{\rho_l}$$

where h = film thickness, t = time, x = spatial co-ordinate, μ = viscosity, γ = surface tension, J = mass flux across interface, ρ_i = liquid density, ρ_v = vapor density. In this equation, temperature controls the viscosity, surface tension, densities as well as the mass flux across the interface. In general, these properties are dependent on the material design and often involve a trade-off. For example, resist materials diluted by solvent have lower viscosity than those that are undiluted, as seen in the XNIL26 family of resists from MicroResist Technologies. However, the diluted materials are also more volatile. Hence, this equation can be used to derive desirable material properties to achieve a desirable process time scale.

[00100] In addition, a linear stability analysis needs to be conducted for this equation to determine the influence of temperature. One goal is to understand if a uniform film would remain uniform, and how any non-uniformities would develop with parametric variation in fluid properties as well as film thickness and temperature profiles. In addition to evaporation, other dispersion and mixing characteristics may also be exploited to further influence thin film evolution.

[00101] Preliminary understanding of thin film flows in the presence of evaporation and surface tension gradients can be understood with the help of a linear stability analysis. Work done in the literature suggests that, for diffusion-limited flows, i.e., flows in which the local ambient is saturated with the vapor near the interface and evaporation is limited by diffusion of the vapor, any local film thickness perturbations are damped. This implies that non-uniform films will tend to become uniform in the absence of local substrate topography. On the other hand, for transfer-limited flows, i.e., flows in which there is advection at the interface that prevents the vapor from being saturated at the interface, the flow is unstable. This implies that troughs and valleys get amplified, which renders the film increasingly non-uniform. In the context of a PFIL process, both these situations can be potentially exploited. The diffusion-limited case would likely offer stable control of the film thickness variations in initially non-uniform films, such as in IJ-PFIL. But, the transfer-limited case can be used to generate non-uniformities that can enable filling of directional patterns, or in SC-PFIL and SD-PFIL, where the initial film is substantially uniform. However, in both these cases, the exact time scales are important, which can be found through a thorough analysis of typical process parameters.

[00102] A model enhancement for IJ-PFIL is now discussed.

[00103] Because the resist solution is assumed to be highly wetting, the above lubrication model holds for both individual drops as well as multiple drops that have merged to form a film. However, the boundary conditions for the case with only a single drop or very few merged drops are much more complex than the case where several thousands of drops have merged to form a contiguous film. This is also because of random perturbations that can change film thickness, pressure or temperature conditions. Hence, for the stages of drop spreading and merging, results from this model can be complemented with experimental heuristics to drive the inverse optimization scheme. The use of heuristics can also help with highly directional patterns. For example, in the domain of inkjet printing, uniform width lines are routinely formed by merging multiple drops. A stability criterion has been established to determine when such lines are stable and when they lead to defects, as shown in Figure 12 discussed below. Such heuristics can be used to tweak drop pitch to enable stable film formation, assuming there is no evaporation in the spreading and merging stages. Moreover, for directional patterns, the process can be repeated after solvent evaporation, to get defined stable lines over the continuous film that are parallel to the directionality of the pattern.

[00104] Referring now to Figure 12, Figure 12 illustrates a stable bead formation in accordance with an embodiment of the present invention. The x-axis of Figure 12 is a function of drop spacing and contact angle, while the y-axis is a function of printhead velocity and fluid material properties.

[00105] A model enhancement for SC-PFIL is now discussed. Process modeling for the spin-coating process can rely on well-established experiments to determine relation of film thickness with different process control parameters. Some of these experimentally derived relations are shown in Figure 13. Figure 13 illustrates variation of film thicknesses with spin time and spin speed in accordance with an embodiment of the present invention. The spin-coating process has three stages: deposition and spin-up, spin-off and film drying. The first two stages are not amenable for process control but the third stage, where a continuous film has been formed and the film thickness is continuously decreasing because of evaporation from the free surface, does offer some potential for control.

[00106] A model enhancement for SD-PFIL is now discussed.

[00107] Although the slot die coating process primarily offers uniform films, there is evidence in the literature to suggest transient control of the slot die coating process. The first is a conference presentation (Mark Miller, "Intermittent Coating," Presented at the 17th International Coating Science and Technology Symposium) on intermittent slot die coating, i.e., slot die coating of rectangular patches with multiple start-stop transitions without defects, and shows that there are a number of parameters that need to be controlled to maintain defect-free stop and start of coating. The second is a journal article (Romero et al., "Response of Slot Coating Flows to Periodic Disturbances," Chemical Engineering Science, Volume 63, Issue 8, April 2008, Pages 2161-2173, ISSN 0009-2509, http://dx.doi.org/10.1016/j.ces.2008.01.012) where the authors have conducted a perturbation analysis for the final wet film thickness on coating gap and upstream pressure variations. They report that the wet film thickness variation has a phase shift from the coating gap variation. The film thickness variation amplitudes are usually damped, but at high perturbation frequencies (~1 KHz), there can be high-amplitude oscillations in the wet film thickness. Thus, it is important to capture the effect of these transients so that they can be used effectively for local film thickness management, which may become important if a substantially uniform film may not lead to the desired non-uniform film at the end of the downstream controlled evaporation step. However, it is important to note that in the direction parallel to the die, there is little scope for varying the film thickness beyond what is physically possible given the die geometry.

[00108] The slot die coating process, too, can benefit from a prior experimental determination of the process window that can be used to augment the model in the form of heuristics, which can also drive tweaking of the film thickness profile to accommodate directional patterns on the template.

[00109] A discussion regarding the metrology and feedback for process optimization is now deemed appropriate.

[00110] While most process optimization involves off-line metrology and operator-based process tuning, they are difficult to implement for P-FIL because of highly coupled multi-input control systems and a limited process window. It is difficult for operators – even with significant domain experience – to handle the large numbers of combinatorial choices in a systematic manner to enable defect-free execution of the process. Here it is proposed to leverage recent

research in extending the resolution limits of piezo inkjetting systems, such as disclosed in Snyder et al., "Analog Drop Volume Control for Piezoelectric Inkjets," 2016 ASPE Annual Meeting, Portland, Oregon, October 23-28, 2016, which is incorporated by reference herein in its entirety, by using real-time sensing as feedback for the process in order to obtain optimum parameters. This feedback mechanism can work with a validated model of the process or with the actual machine in the loop should the forward or inverse model become intractable. In such situations, real-time process feedback may be used on its own to run "model-free" optimization, or may be used to enhance the existing model. In one embodiment, in-line metrology is used to provide feedback for optimization using a machine in a loop control. In one embodiment, the in-line metrology uses one or more of the following: visual feedback, optical feedback, electro-magnetic feedback and thermal feedback. In one embodiment, the in-line metrology is performed using an array of microelectromechanical systems (MEMS)-based Atomic Force Microscopes (AFMs) with individual control of a location of each AFM tip. In one embodiment, the array of AFM tips has individually addressable locations. In one embodiment, an optimum positioning of the array of AFM tips on a wafer with a pattern, a topography variation or a variation in a thickness of a film(s) is determined. Each AFM tip in the array of AFM tips provides data that is aggregated to infer a pattern, a topography variation or a film thickness variation. The wafer may be scanned to measure the pattern, topography variation or film thickness variation. The measured pattern, topography variation or film thickness variation is aggregated and analyzed to infer the pattern, topography variation or film thickness variation. In one embodiment, each AFM tip of the array of AFM tips is on a different device on the same wafer. In one embodiment, each of these different devices is the same.

[00111] With respect to real-time or near-real-time sensing, the process metrics that ensure reliable coating include mean and standard deviation of coating thickness over large areas, and avoidance of defect mechanisms. Current off-line metrology approaches are too slow to be incorporated in real-time process control as nanoscale measurements have to be made over centimeter scales resulting in a high-dimensional multi-scale metrology problem. New sensing architectures that are designed in conjunction with process models can be used to significantly enhance the speed of sensing and detection of process parasitics and defects. Optical techniques, such as film thickness reflectometry, ellipsometry, spectrometry, etc. are typically used in manufacturing processes as they can be fast (relative to tip-based mechanical techniques,

electron microscopy, etc.) and are often non-destructive. The precision and speed trade-offs can be properly understood with careful modeling. For example, lower spatial and spectral resolution of optical techniques can increase sensing speed and models to help users understand the corresponding loss of sensed information and its potential impact on process yield.

[00112] For example, in IJ-PFIL, the sensing can happen very close to the nozzle and before the drop sits on the substrate. For SD-PFIL, too, a camera can be collocated with the die to capture the coating bead formation. However, it may be challenging as the coating gap is much smaller (<10 X) than the distance between the nozzle and the substrate in a typical inkjetting environment. For SD-PFIL, then, it may be easier to capture the bead after it has been coated on the substrate to look for defects or other signatures. This can also be done using optical techniques and model-based image processing algorithms.

[00113] Planarization of feature transitions, such as step heights, presents a challenge. This is because, such sharp transitions entail a change in fluid and solid mechanical behavior, which is difficult to characterize in robust models, and which require in-situ validation. Moreover, the use of high throughput optical film thickness metrology, which works well for bulk films without sharp thickness changes within the optical spot size, is not compatible with measuring film thickness changes in the immediate vicinity of such steps. This entails the use of relatively slow tip-based surface profiling techniques, such as atomic force microscopy (AFM). In this disclosure, the use of an array of AFMs with the ability to automatically reconfigure individual AFM tip locations and scan regions is presented. One embodiment for creating these automatically reconfigurable arrays is to use a Si-micro chip based AFM MEMS device. The use of an AFM for offline characterization in production environments for semiconductor fabrication is provided by Bruker Sciences.

[00114] The present invention extends the idea of the AFM array for planarization with the ability to reconfigure the location of each AFM tip in the array based on the pattern layout across a full field (typically 26 mm x 33 mm), typically obtained from a GDS file. More specifically, knowing the GDS file of the prior pattern(s), the prior pattern's etch depth and any subsequent film deposition on that pattern, a knowledge of the specific regions where planarization would be a challenge, could be inferred *a priori* through empirical or computational models, or a combination of the two. The AFM array could then be reconfigured to specifically measure in

those challenging regions. This way, the AFM array can rapidly measure the film thickness profile in the vicinity of critical step transitions. Additionally, the AFM array can be devised such that it is reconfigurable across an entire wafer, rather than a single field. This is because most fields in a silicon wafer undergoing routine lithography processing, are substantially similar. The AFM array can then be arranged such that a single AFM tip has the range to address a single field. Different AFM tips can then measure different features on the substantially similar field, with each feature being on a different field. Aggregating these measurements can then provide a picture of the surface of a field. If a different field layout is then processed, the same AFM array can be reconfigured to enable metrology of the new layout. This embodiment is applicable to U.S. Patent No. 9,415,418, which is incorporated by reference herein in its entirety.

[00115] Furthermore, machine-in-the-loop forward models, validated numerical simulations and stochastic optimal control techniques based on genetic algorithms (GA) can be used to develop sophisticated control algorithms for the P-FIL process. A hierarchical approach can be used to gradually increase the number of control variables to be included in the optimized control algorithm. For example, a sensing and actuator framework of low complexity can be first used to develop GA based process control schemes. The complexity of sensing (e.g., the spatial and spectral resolution of optical sensing) and actuator framework (e.g., number and resolution of control variables) can be gradually increased, as needed, and the GA based process control schemes can be established. At the same time, it is important to note that for IJ-PFIL, for example, inkjet parameters can be changed on the fly because of the 'drop-on-demand' nature of the process. However, the same cannot be said for SD-PFIL or SC-PFIL. There is a non-zero time constant associated with changing process parameters. Understanding and capturing this transient behavior is used in the controllability of the system.

[00116] A discussion regarding material design is now deemed appropriate.

[00117] The formulation design consists of imprint resist comprising of considerable amount of components having similar volatility, dissolved in a solvent that is considerably more volatile than the rest of the components. The solvent role is to dilute the required quantity of imprint resist to higher volume thus allowing for better way of spreading small amounts of imprint resist over the substrate in IJ-PFIL, and managing the final dry film thickness starting from a much

thicker initial wet film in SC-PFIL or SD-PFIL. Once the imprint resist solution is dispensed on the substrate, the solvent evaporates first while the rest of the components evaporate at much lower rate due to their lower volatility. This results in a mixture containing higher concentration of the other components and residual or negligible amounts of solvent. The remaining, solvent-depleted liquid is then selectively evaporated leaving a substrate containing areas with controlled imprint resist distribution. After the proposed scheme of selective evaporation, the final ratio of the remaining components may not be the same as the initial ratio of the same components in the resist formulation. Furthermore, the components ratios may not be the same on various spots across the substrate after selective evaporation. However, appropriately formulated systems may perform satisfactorily under a range of compositions. Formulation design may take into account the expected amount of material that needs to be evaporated, such that the optimum range of component ratios is not disrupted. Further, certain components, such as the photoinitiator or crosslinkers, will almost always be less volatile, as seen in the table below.

[00118] Besides solvents, an imprint resist formulation may contain a mixture of some, or all the following components: an initiator; polymerizable monomers with one active group; polymerizable monomers with more than one active group referred to in the art as crosslinkers; and surfactants. This list is not exhaustive as other components may be present according to desired performance and applications.

[00119] Example for relevant components is shown in the table below:

Role	Material	Boiling Point [^{O}C at 1 atm]
Monomers	2-Ethylhexyl methacrylate	218
	Cyclohexyl methacrylate	210
	Isobornyl methacrylate	258

	Tetrahydrofurfuryl methacrylate	222
	Benzyl methacrylate	243
Crosslinker	Ethylene glycol dimethacrylate	240
Surfactant	1H,1H,2H,2H-Perfluorodecyltriethoxysilane	209
Photoinitiators	Irgacure 184	>300
	Irgacure 819	>300
	Irgacure 2959	>300
Solvent	MIBK Ethyl acetate	117 77

[00120] Downstream process considerations may preclude the use of UV-crosslinkable polymers, particularly in the application of planarization, which does not require a patterning resist material. For example, most methacrylate polymers have a Tg of ~ 150° C. Any downstream thermal processing beyond 150° C may damage the material. There are other thermoset polymers, such as polyimide, that have a much higher Tg of ~350° C. Hence, the practice of planarization using this polymer can alleviate concerns with thermal processing. But these materials are also highly viscous, which makes them difficult to coat or inkjet with substantially lower volumes. To achieve this, the polyimide material can be diluted in a solvent, which can reduce their viscosity and make the material amenable to coating and/or inkjetting. The solvent will need to be completely evaporated to minimize condensation on the substrate. This can be done by using a solvent with substantially higher volatility (e.g., MIBK, ethyl acetate) and using a heated substrate chuck or IR lamps to completely and rapidly evaporate the solvent. After solvent evaporation, the polymer can then be baked or cured on the substrate. For

the sake of this disclosure, the liquid formulation (or "liquid resist formulation") used for this purpose is also called a "resist," having a solvent component and one or more non-solvent components.

[00121] If the substrate material is not compatible with significant temperature changes, especially if the non-solvent components of the resist require high boiling points, one embodiment of the invention can involve the use of partially evacuated chambers to reduce the boiling points of the resist components. Another embodiment can involve the use of a chuck or mount for the substrate which is substantially maintained at a constant temperature which is below the boiling points of the resist components. This chuck or mount can be metallic to enable rapid dissipation of any heat that is transferred to it from the substrate and thereby allow the substrate to substantially maintain its temperature, even in the presence of dynamic heat loads during the selective evaporation process. Another embodiment of the invention involves the use of one or more material films between the substrate and the resist material. These films could be chosen such that their combination would lead to near zero transmission of electro-magnetic radiation in the infrared spectrum to the substrate, thereby preventing the substrate from heating, but can themselves absorb the heat without suffering any damage. An exemplar film material is CVD Carbon or Spin-on-Carbon. These materials may additionally also be used as sacrificial films when transferring the resist pattern onto the substrate.

[00122] Additional material considerations for planarization include the use of silicon or carbon containing materials that facilitate good mechanical properties, such as elastic modulus, elongation to fail and failure strength. Also, the embodiment of free-surface planarization can use a low-viscosity silicon-containing resist material as discussed in Lin, M.W., "Simulation and design of planarizing materials and interfacial adhesion studies for step and flash imprint lithography", Ph.D. Dissertation, The University of Texas at Austin, 2008. This material can enable a high initial degree of planarization which can be further improved through selective evaporation of the resist material.

[00123] There are various applications in nanophotonics that can result from using the principles of the present invention. Exemplar nanophotonic devices include wire-grid polarizers and metamaterials, such as flat lenses. These devices typically involve fabrication of nanostructures made of metals (Al, Au, etc.) or dielectrics (SiO_2, Si_3N_4, TiO_2, etc.). For example, wire-grid

polarizers for display applications require nanoscale patterns made of aluminum. Such polarizers can be fabricated using one of two approaches. In the first approach, a polymer resist line/space pattern can be obtained using the PFIL process. This can be followed by Glancing Angle Deposition of Al on the line/space pattern such that the metal remains discontinuous. The second approach involves deposition of an Al film using vacuum-based processes, such as e-beam evaporation, followed by the imprinting of a polymer resist line/space pattern using PFIL. This is then followed by a descum etch of the residual layer using O_2 plasma and etching of the underlying Al film using Cl-based plasma chemistry.

[00124] Metamaterials, such as flat lenses, have been discussed in the context of enabling interaction of visible light with nanoscale patterns to achieve phenomena that are otherwise impossible in the absence of nanoscale patterns. Flat lenses, for example, enable the 'refraction' of light from flat surfaces, that would otherwise have required some curvature. These lenses are enabled by fabricating specific nanoscale patterns on the flat surface that interact with incoming light to result in refraction. These nanoscale patterns are made of high-index dielectric materials, most notable, TiO_2. Such flat lenses can be made using PFIL in combination with other nanoscale fabrication techniques. One approach for the fabrication of flat lenses involves imprinting the negative of the desired TiO_2 pattern with a polymerized resist using PFIL. This is followed by slot-die coating of a sol-gel TiO_2 precursor, which fills the resist "mold" and forms a continuous film at the top. This continuous film of the TiO_2 precursor can be etched using reactive ion etching in a O_2/Ar/F based plasma. Alternatively, the features on this resist pattern can be modified at the top to make them tapered. Such structures can be fabricated using multi-tiered templates fabricated for imprint lithography. This would allow the sol-gel TiO_2 precursor to substantially fill the resist mold without forming a substantially continuous film at the top, provided the volume of the precursor is tightly controlled in the slot-die coating process. Another approach can involve conformal Chemical Vapor Deposition or Atomic Layer Deposition of TiO_2 to fill the resist mold, followed by an etch-back of the continuous TiO_2 film at the top of the mold. In all cases, the resist pattern can be removed using O_2 plasma.

[00125] After fabrication of these nanophotonic devices, it may be necessary to also encapsulate them with barrier films to prevent diffusion of water vapor, oxygen or other materials that can damage the devices. Encapsulation can be done by using vacuum-based vapor deposition

techniques that preferentially accumulate material at corners and thereby cap the top of the nanoscale features while leaving an air gap below them and between successive features.

[00126] A discussion regarding fabricating nanoscale patterns made of high-index dielectric materials, such as TiO_2, on a flat surface is provided below in connection with Figures 14 and 15A-15D.

[00127] Figure 14 is a flowchart of a method 1400 for fabricating nanoscale patterns made of high-index dielectric materials, such as TiO_2, on a flat surface in accordance with an embodiment of the present invention. Figures 15A-15D depict the cross-sectional views of fabricating nanoscale patterns on a flat surface using the steps described in Figure 14 in accordance with an embodiment of the present invention.

[00128] Referring to Figure 14, in conjunction with Figures 15A-15D, in step 1401, resist 1501 is patterned on a substrate 1502 as shown in Figure 15A.

[00129] In step 1402, a short descum ash is performed to expose substrate 1502 as shown in Figure 15B.

[00130] In step 1403, substrate 1502 is slot-die coated with TiO_2 1503 or, alternatively, TiO_2 1503 is deposited on substrate 1502 via chemical vapor deposition as shown in Figure 15C.

[00131] In step 1404, a blanket etch of TiO_2 1503 is performed as shown in Figure 15D.

[00132] The descriptions of the various embodiments of the present invention have been presented for purposes of illustration, but are not intended to be exhaustive or limited to the embodiments disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the described embodiments. The terminology used herein was chosen to best explain the principles of the embodiments, the practical application or technical improvement over technologies found in the marketplace, or to enable others of ordinary skill in the art to understand the embodiments disclosed herein.

CLAIMS:

1. A method for fabricating patterns on rigid wafer substrates, the method comprising:

implementing an inverse optimization scheme to determine process parameters used to obtain a desired film thickness of a liquid resist formulation, wherein said liquid resist formulation comprises a solvent and one or more non-solvent components;

covering a substrate with a substantially continuous film of said liquid resist formulation using spin-coating, wherein said liquid resist formulation is diluted in said solvent;

evaporating said solvent substantially from said liquid resist formulation forming a film;

closing a gap between a template and said substrate;

curing said film to polymerize said film; and

separating said substrate from said template leaving said polymerized film on said substrate.

2. The method as recited in claim 1, wherein said liquid resist formulation, whose solvent has already been evaporated, is selectively evaporated to form said film with an intentionally non-uniform profile to match a desired thickness profile prior to closing said gap between said template and said substrate.

3. The method as recited in claim 2, wherein said selective evaporation is carried out by one or more of the following: a temperature controlled substrate chuck, an array of individually controllable infrared lamps, an array of individually controllable fans to control air flow, individually controllable micro heaters or coolers on said substrate, and a spatial light modulator to control one or more sources of electromagnetic radiation.

4. The method as recited in claim 3, wherein said spatial light modulator comprises one or more digital micromirror device (DMD) arrays.

5. The method as recited in claim 2, wherein said selective evaporation is carried out in an environment with controlled vapor pressures.

6. The method as recited in claim 1, wherein evaporation and patterning are carried out in separate stations.

7. The method as recited in claim 1, wherein a stack of one or more films is used between said liquid resist formulation and said substrate that substantially absorbs electromagnetic radiation.

8. The method as recited in claim 1, wherein said inverse optimization scheme is further augmented to determine one of the following: a spatial evaporation profile, a spatial temperature profile, a spatial material removal profile, a spatial evaporation rate profile, and a spatial material removal rate profile.

9. The method as recited in claim 1, wherein in-line metrology is used to provide feedback for said inverse optimization scheme using a machine in a loop control.

10. The method as recited in claim 9, wherein said in-line metrology uses one or more of the following: visual feedback, optical feedback, electro-magnetic feedback and thermal feedback

11. The method as recited in claim 1, wherein said inverse optimization scheme comprises one or more of the following: genetic algorithms, simulated annealing, and full pattern search to achieve an objective function of minimizing an error between a function of a desired film thickness and said obtained film thickness.

12. The method as recited in claim 11, wherein a forward model is used as a core for said inverse optimization scheme to predict a film thickness profile, wherein said forward model incorporates one or more of the following: thermal transport, solute transport, and solvent transport.

13. The method as recited in claim 1, wherein said liquid resist formulation consists of said solvent with substantially higher volatility than the rest of the components of said liquid resist formulation.

14. The method as recited in claim 1, wherein said one or more non-solvent components of said liquid resist formulation have substantially similar volatility.

15. The method as recited in claim 1, wherein said one or more non-solvent components of said liquid resist formulation except for a photoinitiator have a boiling point that differ by less than 30° C.

16. The method as recited in claim 1, wherein said one or more non-solvent components of said liquid resist formulation except for a photoinitiator have a boiling point that differ by less than 10° C.

17. The method as recited in claim 1, wherein said one or more non-solvent components of said liquid resist formulation except for a photoinitiator have a boiling point that differ by less than 5° C.

18. The method as recited in claim 1 further comprising:

keeping an expected loss of material of said liquid resist formulation and subsequent changes in component concentration of said liquid resist formulation within an optimum range.

19. The method as recited in claim 1, wherein said inverse optimization scheme compensates for sequentially selective evaporation from one or more digital micromirror device (DMD) arrays, or temperature profiles resulting from heat capacity of said substrate or material, or deterministic changes in a film thickness profile due to known changes in ambient conditions or when handling or transporting said substrate.

20. The method as recited in claim 1, wherein an inkjet is used to dispense discrete drops of said diluted monomer which does not form a substantially continuous film to locally modify film thickness profiles prior to closing said gap between said template and said substrate.

21. The method as recited in claim 1, wherein said template is patterned with a lateral feature dimension of less than 500 nm.

22. The method as recited in claim 1, wherein said template is patterned with a lateral feature dimension of less than 100 nm.

23. The method as recited in claim 1, wherein said template has one or more of the following: multi-tiered patterns and three-dimensional patterns.

24. The method as recited in claim 1, wherein said template is flexible or held in a roll-to-roll configuration.

25. A method for planarizing patterns on rigid wafer substrates, the method comprising:

implementing an inverse optimization scheme with existing substrate topography as an input which is used to determine process parameters used to obtain a desired film thickness of a liquid resist formulation, wherein said liquid resist formulation comprises a solvent and one or more non-solvent components;

covering a patterned substrate with a substantially continuous film of said liquid resist formulation using spin-coating, wherein said liquid resist formulation is diluted in said solvent;

evaporating said solvent substantially from said liquid resist formulation forming a film; and

curing said film to polymerize said film.

26. The method as recited in claim 25, wherein said liquid resist formulation, whose solvent has already been evaporated, is selectively evaporated to form said film with an intentionally non-uniform profile to match a desired thickness profile.

27. The method as recited in claim 26, wherein said selective evaporation is carried out by one or more of the following: a temperature controlled substrate chuck, an array of individually controllable infrared lamps, an array of individually controllable fans to control air flow, individually controllable micro heaters or coolers on the substrate, and a spatial light modulator to control one or more sources of electromagnetic radiation.

28. The method as recited in claim 27, wherein said spatial light modulator comprises one or more digital micromirror device (DMD) arrays.

29. The method as recited in claim 26, wherein said selective evaporation is carried out in an environment with controlled vapor pressures.

30. The method as recited in claim 25, wherein evaporation and patterning are carried out in separate stations.

31. The method as recited in claim 25, wherein a stack of one or more films is used between said liquid resist formulation and said substrate that substantially absorbs electromagnetic radiation.

32. The method as recited in claim 25, wherein a superstrate is used to cover a top of said film to obtain desired evolution dynamics of said film.

33. The method as recited in claim 32, wherein said superstrate is flexible or held in a roll-to-roll configuration.

34. The method as recited in claim 32, wherein a superstrate thickness profile of said superstrate and geometry are optimized to obtain desired evolution dynamics for a given substrate topography.

35. The method as recited in claim 25, wherein said inverse optimization scheme is further augmented to determine one of the following: a spatial evaporation profile, a spatial temperature profile, a spatial material removal profile, a spatial evaporation rate profile, and a spatial material removal rate profile.

36. The method as recited in claim 25, wherein in-line metrology is used to provide feedback for said inverse optimization scheme using a machine in a loop control.

37. The method as recited in claim 36, wherein said in-line metrology uses one or more of the following: visual feedback, optical feedback, electro-magnetic feedback and thermal feedback.

38. The method as recited in claim 36, wherein said in-line metrology is performed using an array of microelectromechanical systems (MEMS)-based Atomic Force Microscopes (AFMs) with individual control of a location of each AFM tip.

39 The method as recited in claim 25, wherein said inverse optimization scheme comprises one or more of the following: genetic algorithms, simulated annealing, and full pattern search to achieve an objective function of minimizing an error between a function of a desired film thickness and said obtained film thickness.

40. The method as recited in claim 39, wherein a forward model is used as a core for said inverse optimization scheme to predict a film thickness profile, wherein said forward model incorporates one or more of the following: thermal transport, solute transport, and solvent transport.

41. The method as recited in claim 25, wherein said liquid resist formulation consists of said solvent with substantially higher volatility than the rest of the components of said liquid resist formulation.

42. The method as recited in claim 25, wherein said one or more non-solvent components of said liquid resist formulation have substantially similar volatility.

43. The method as recited in claim 25, wherein said one or more non-solvent components of said liquid resist formulation except for a photoinitiator have a boiling point that differ by less than 30° C.

44. The method as recited in claim 25, wherein said one or more non-solvent components of said liquid resist formulation except for a photoinitiator have a boiling point that differ by less than 10° C.

45. The method as recited in claim 25, wherein said one or more non-solvent components of said liquid resist formulation except for a photoinitiator have a boiling point that differ by less than 5° C.

46. The method as recited in claim 25, wherein said one or more non-solvent components of said liquid resist formulation comprise a thermoset polymer with a high glass transition temperature.

47. The method as recited in claim 25, wherein said one or more non-solvent components of said liquid resist formulation comprise silicon or carbon.

48. The method as recited in claim 25 further comprising:

keeping an expected loss of material of said liquid resist formulation and subsequent changes in component concentration of said liquid resist formulation within an optimum range.

49. The method as recited in claim 25, wherein said inverse optimization scheme compensates for sequentially selective evaporation from one or more digital micromirror device (DMD) arrays, or temperature profiles resulting from heat capacity of said substrate or material, or deterministic changes in a film thickness profile due to known changes in ambient conditions or when handling or transporting said substrate.

50. The method as recited in claim 25, wherein an inkjet is used to dispense discrete drops of said diluted monomer which does not form a substantially continuous film to locally modify film thickness profiles prior to closing a gap between a template and said substrate.

51. A method for performing in-situ metrology, the method comprising:

having an array of Atomic Force Microscope (AFM) tips with individually addressable locations;

determining an optimum positioning of said array of AFM tips on a wafer with a pattern, a topography variation or a variation in a film thickness, wherein each AFM tip in said array of AFM tips provides data that is aggregated to infer said pattern, said topography variation or said film thickness variation;

scanning said wafer to measure said pattern, said topography variation or said film thickness variation; and

aggregating and analyzing said measured pattern, said measured topography variation or said measured film thickness variation to infer said pattern, said topography variation or said film thickness variation.

52. The method as recited in claim 51, wherein each AFM tip of said array of AFM tips is on a different device on a same wafer, wherein each said different device on said same wafer is substantially the same.

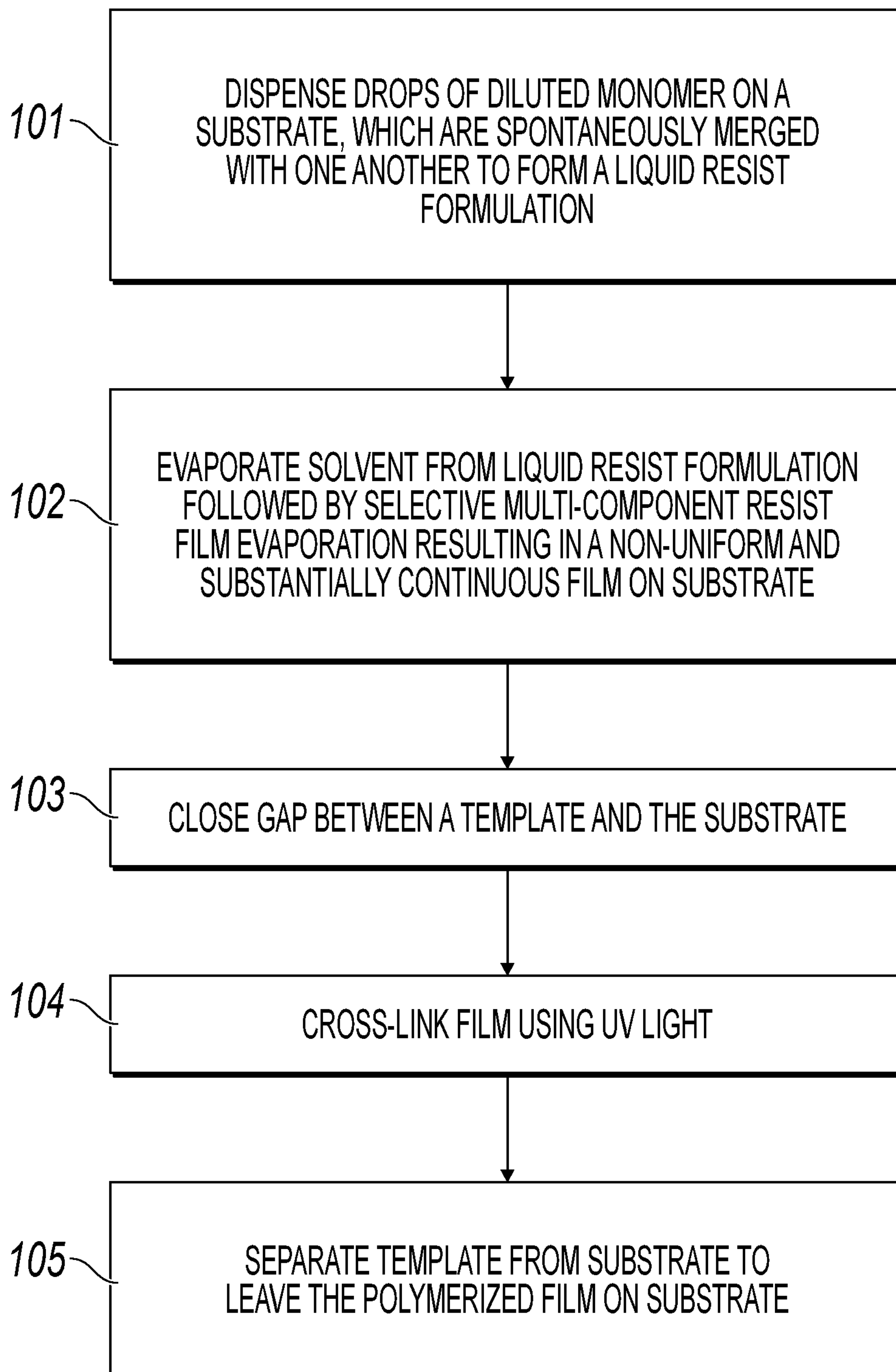


FIG. 1

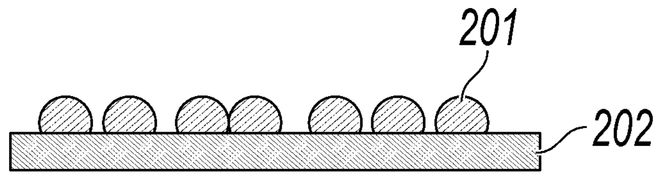


FIG. 2A

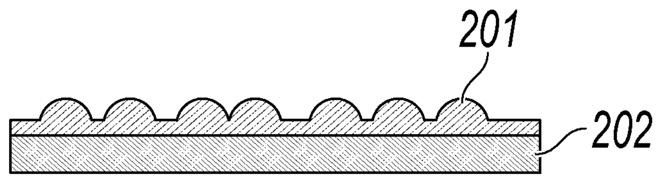


FIG. 2B

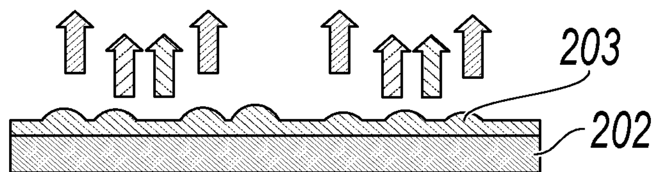


FIG. 2C

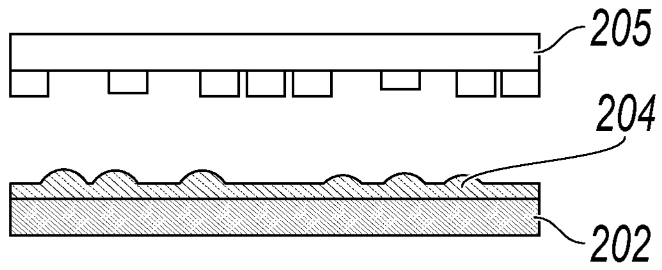


FIG. 2D

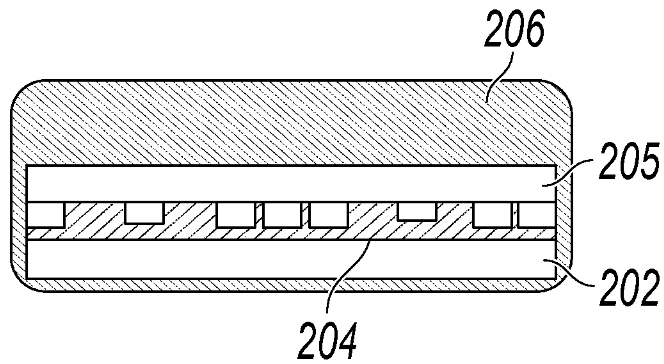


FIG. 2E

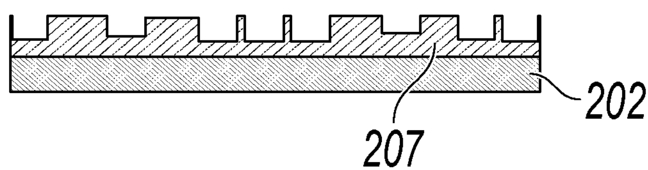


FIG. 2F

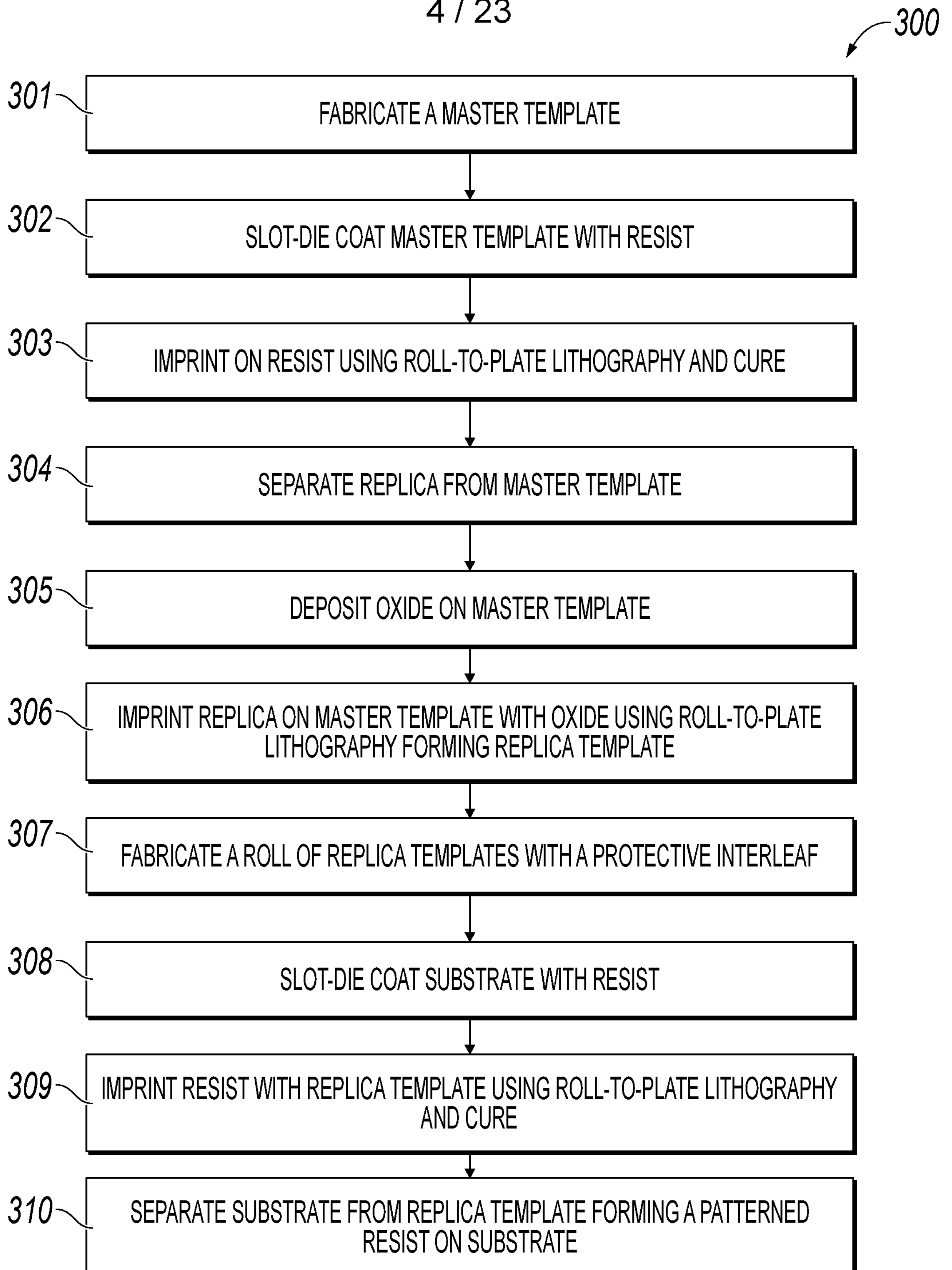


FIG. 3

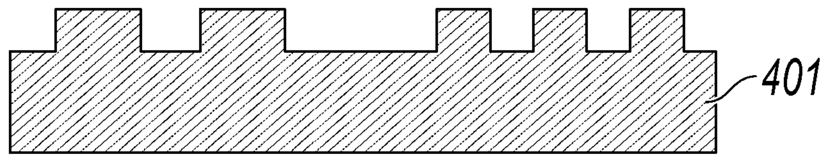


FIG. 4A

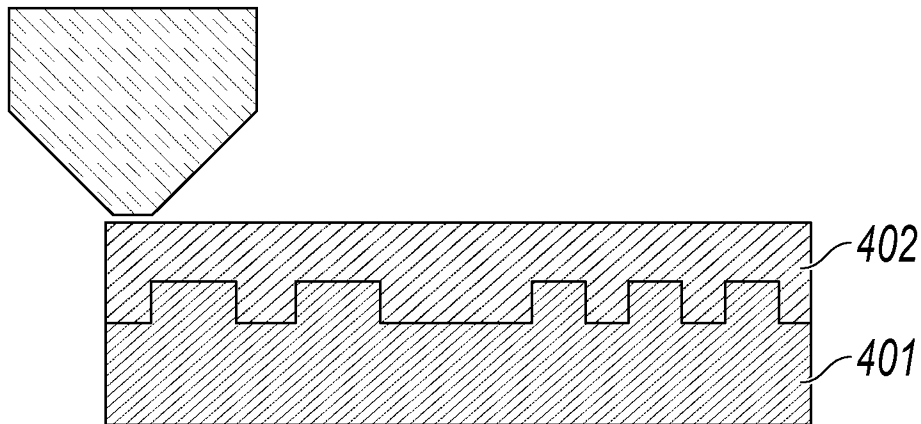


FIG. 4B

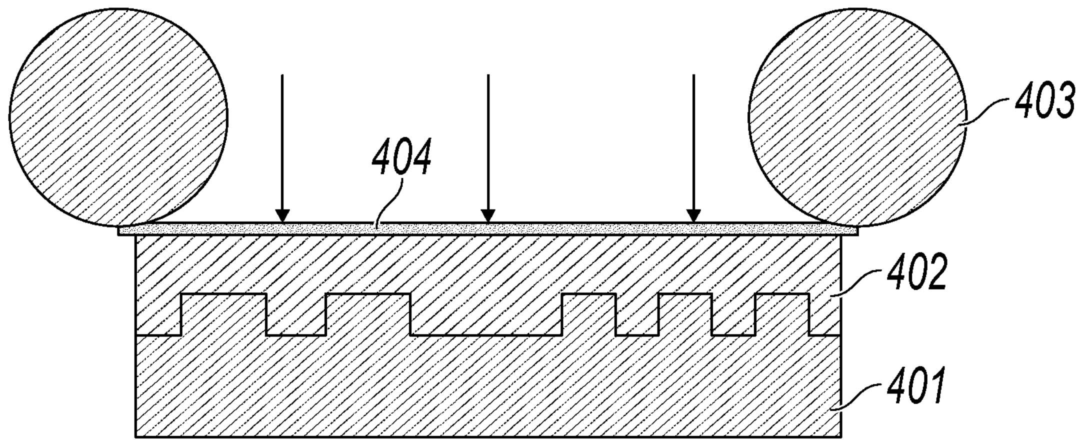


FIG. 4C

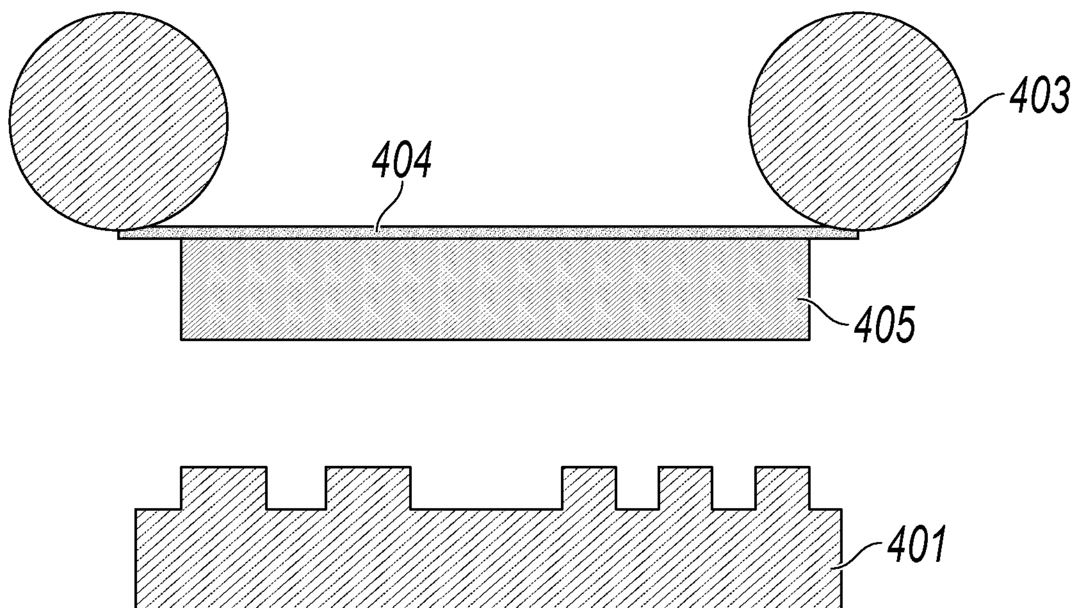


FIG. 4D

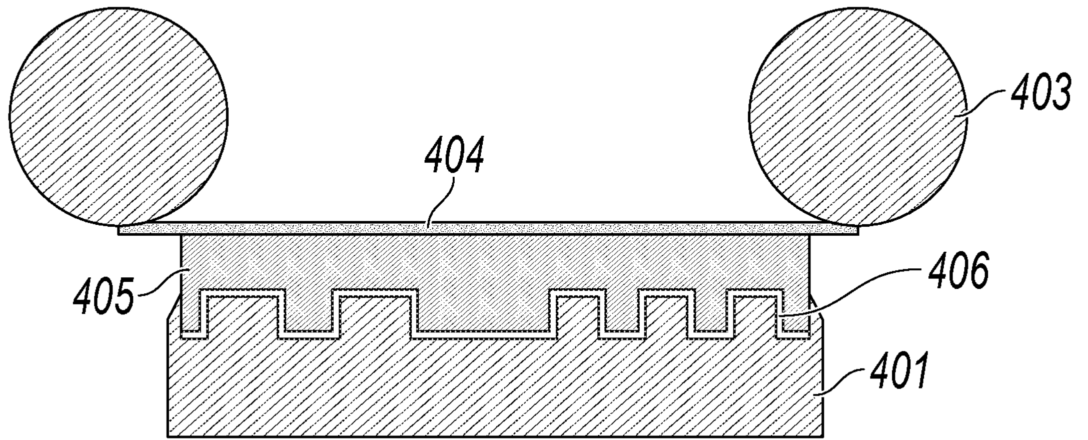


FIG. 4E

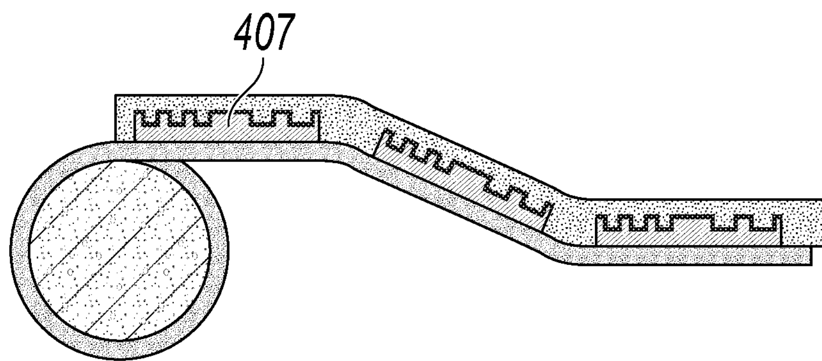


FIG. 4F

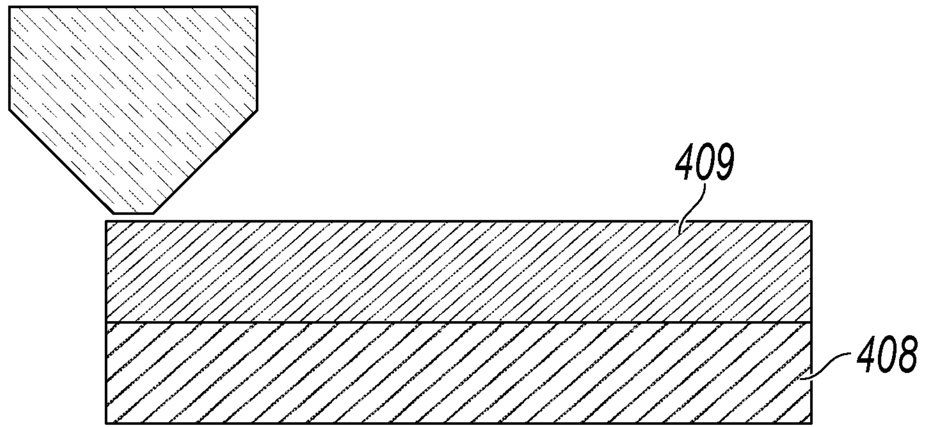


FIG. 4G

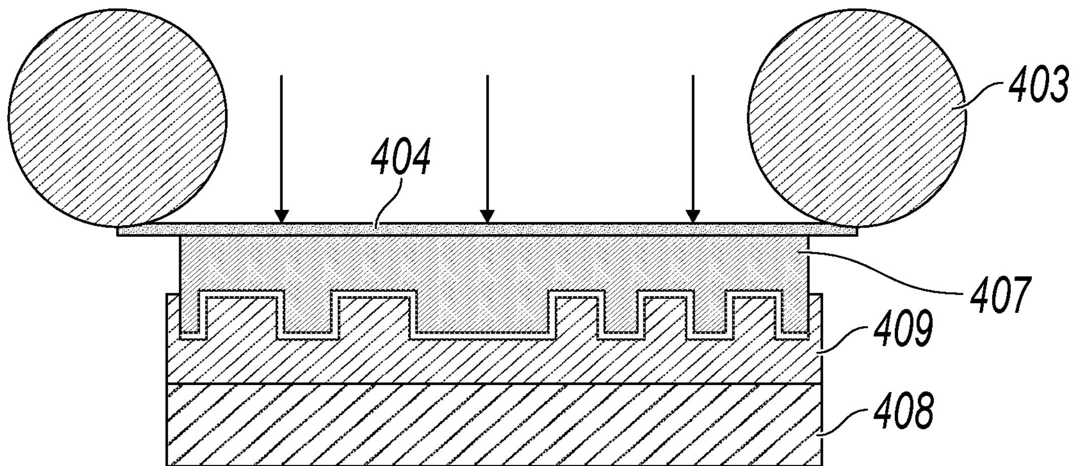


FIG. 4H

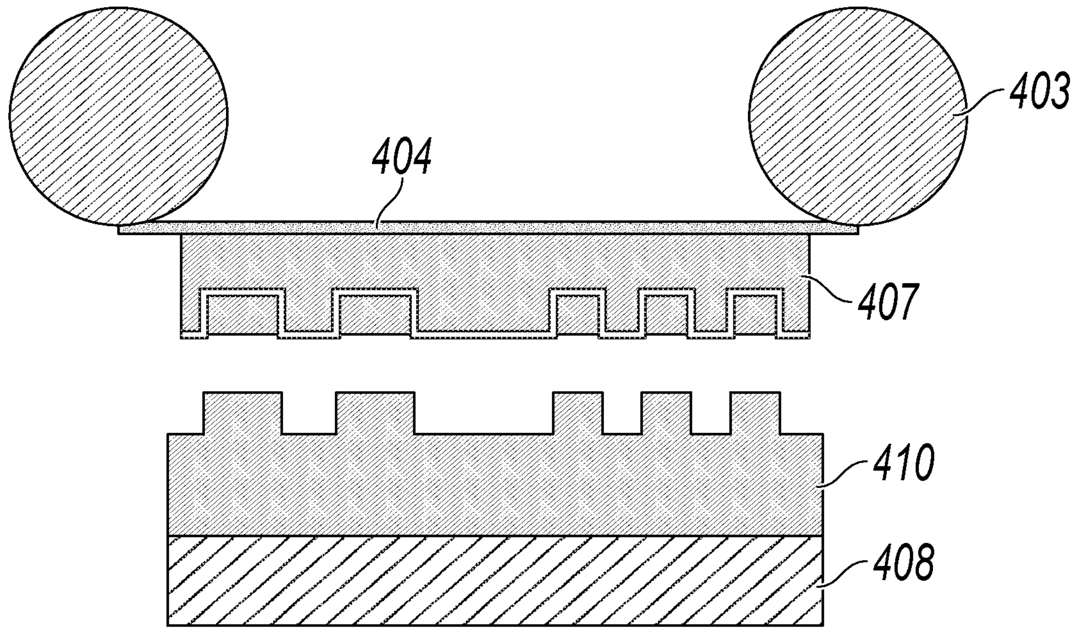


FIG. 4I

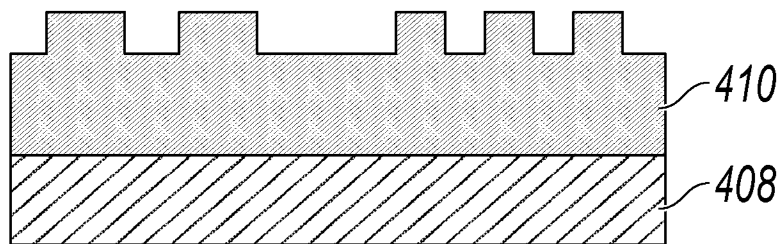


FIG. 4J

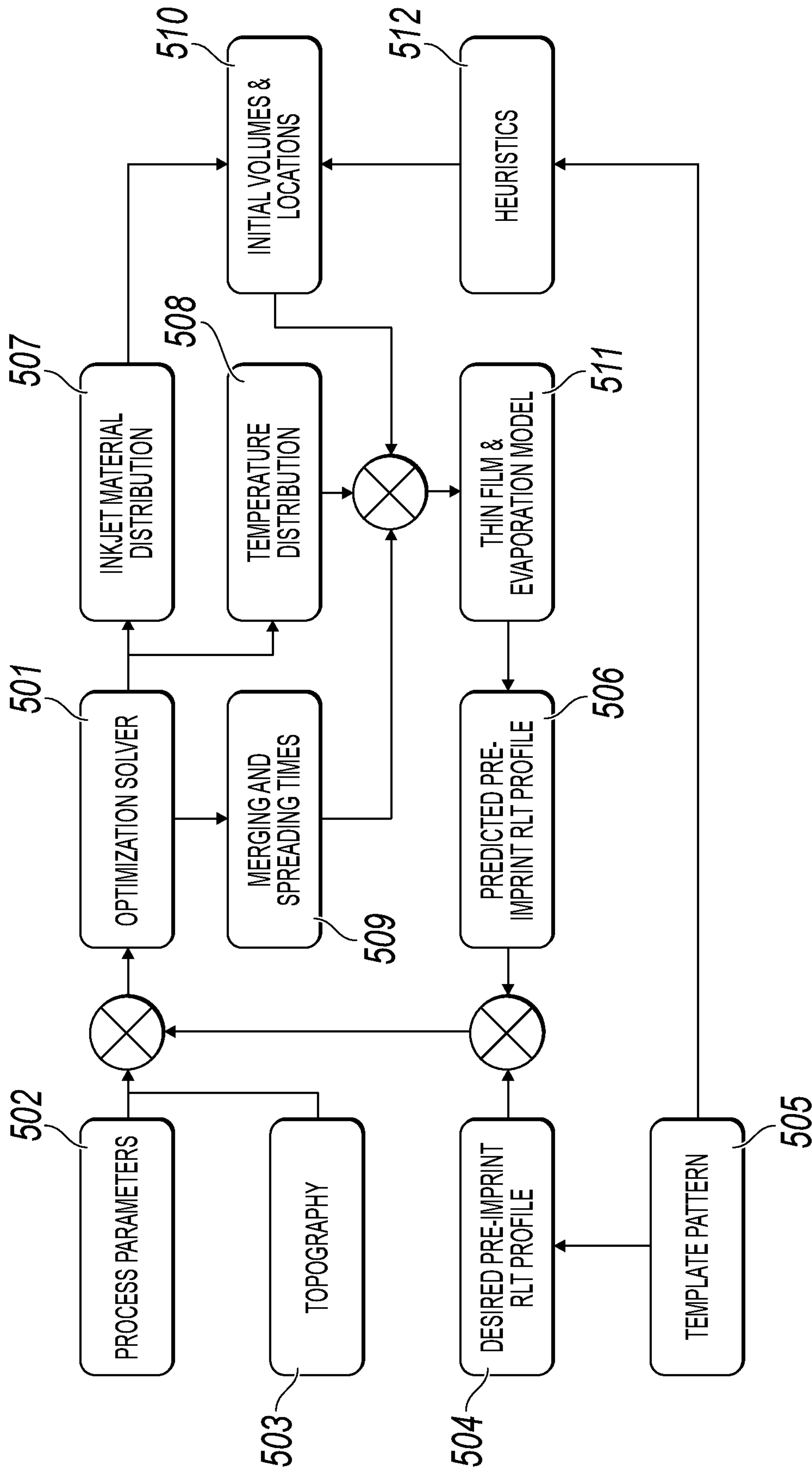


FIG. 5

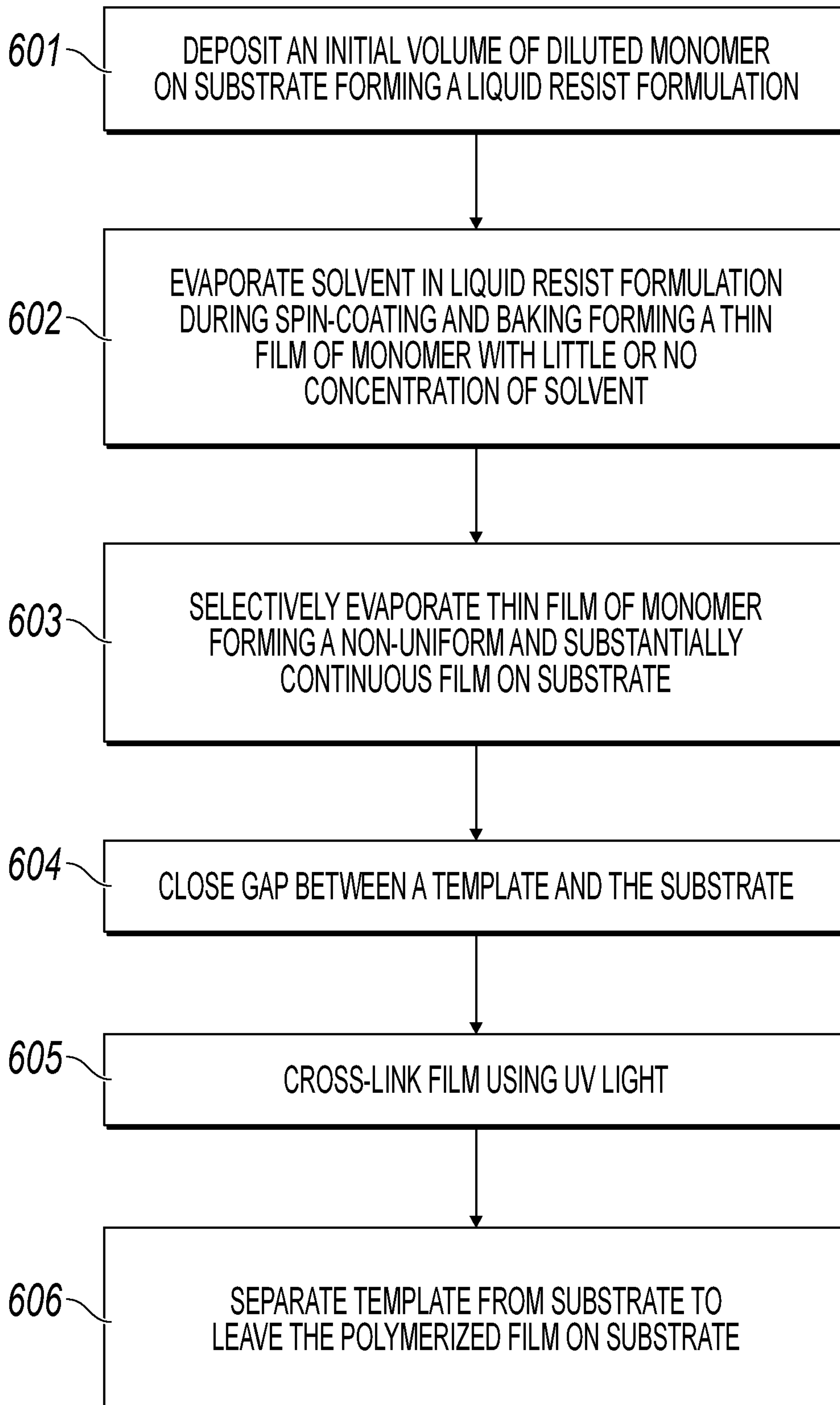


FIG. 6

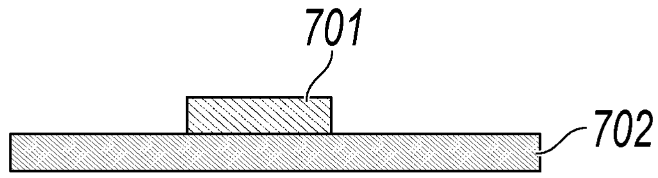


FIG. 7A

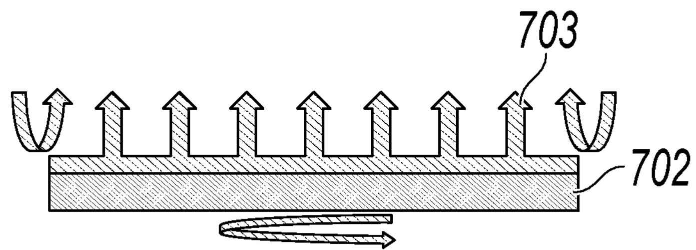


FIG. 7B

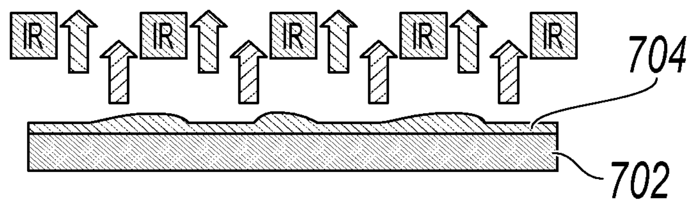


FIG. 7C

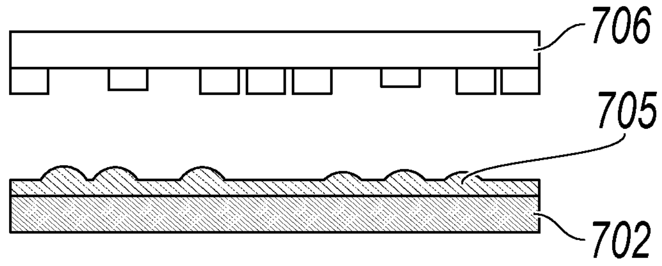


FIG. 7D

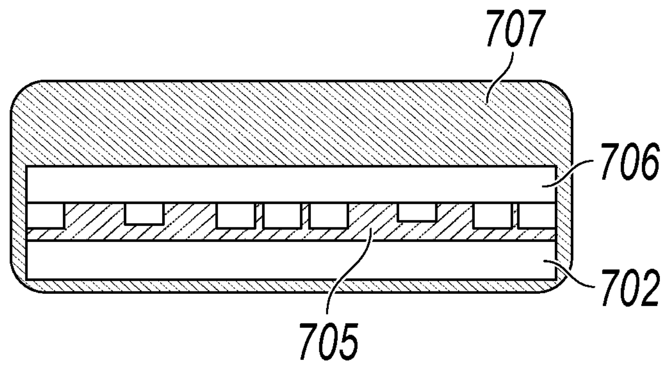


FIG. 7E

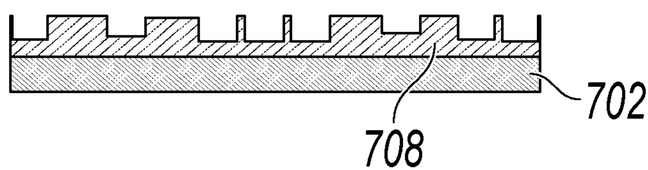


FIG. 7F

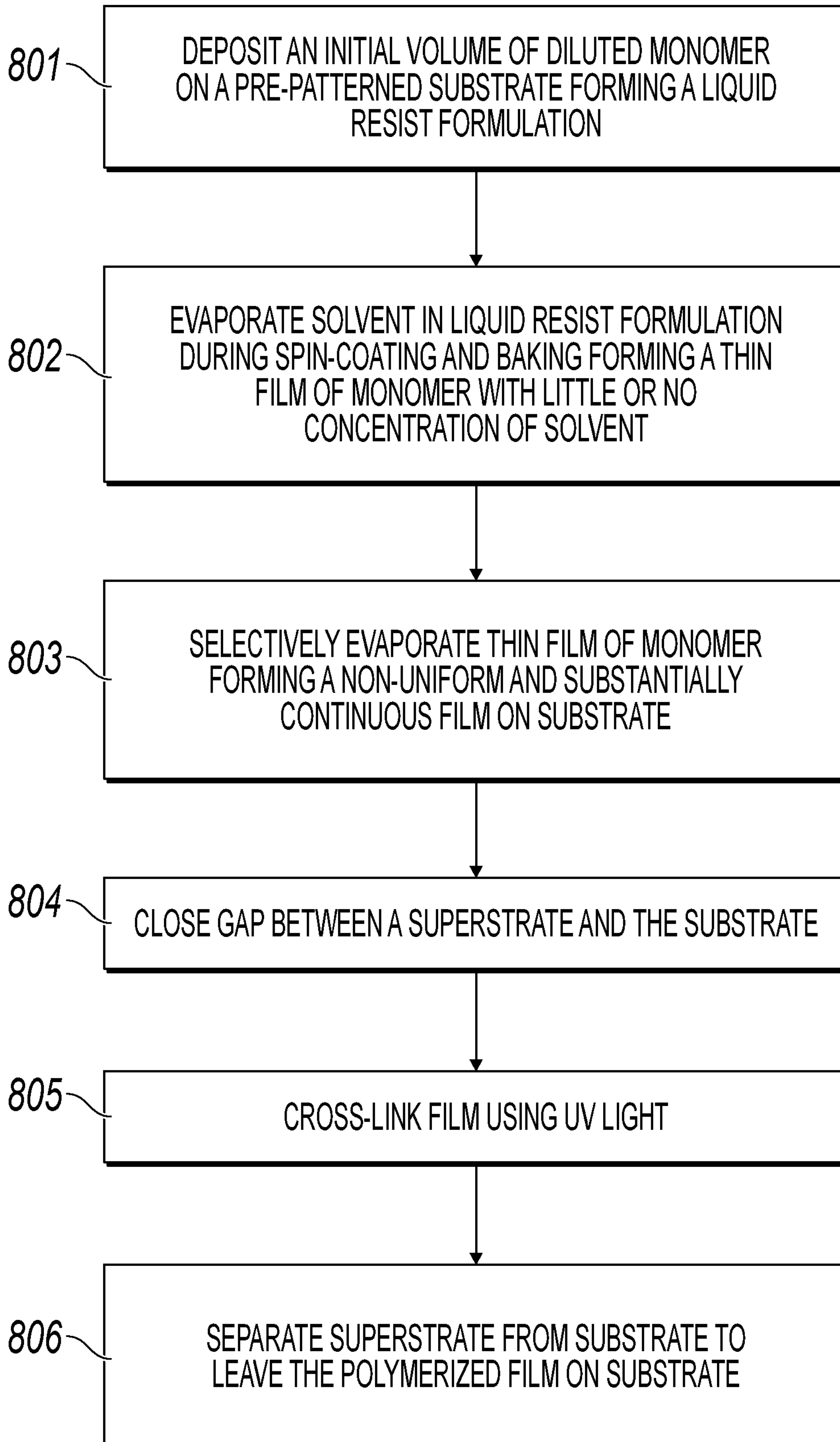


FIG. 8

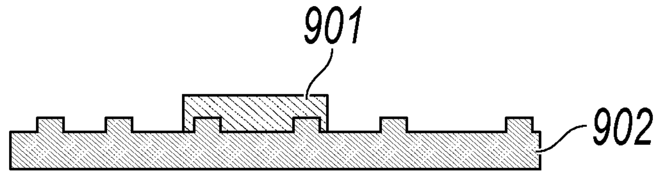


FIG. 9A

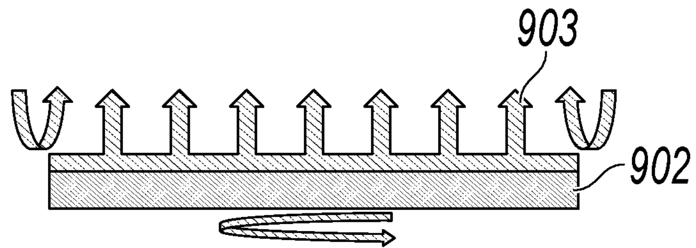


FIG. 9B

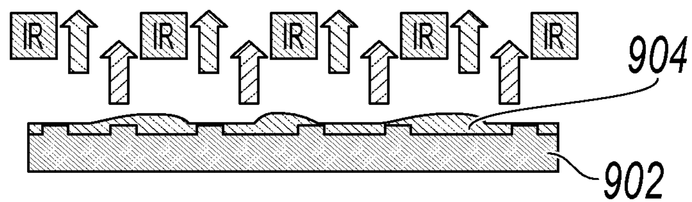


FIG. 9C

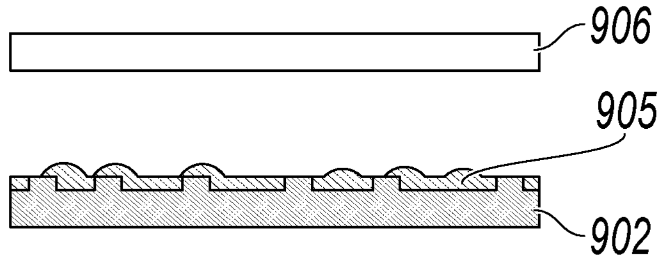


FIG. 9D

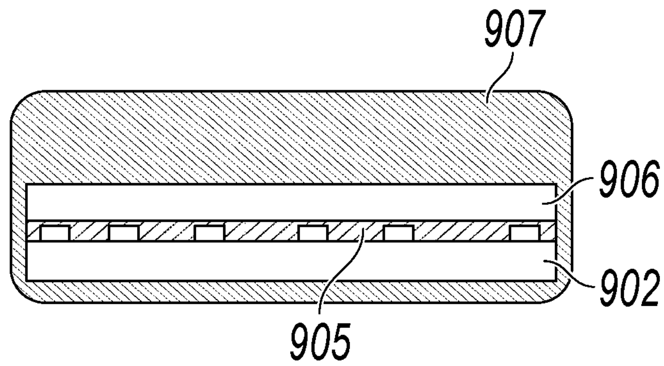


FIG. 9E

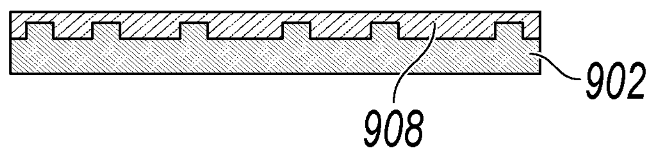


FIG. 9F

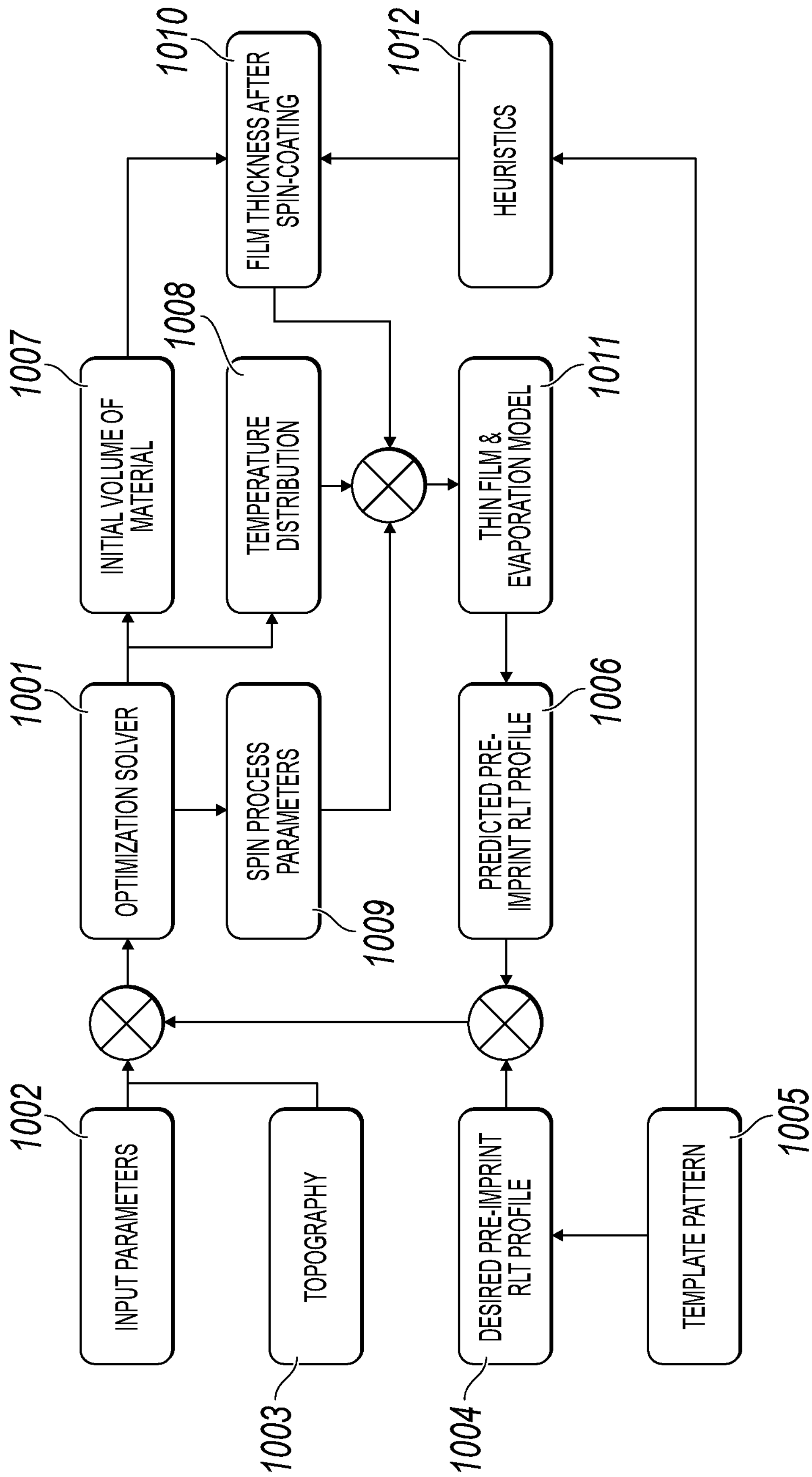


FIG. 10

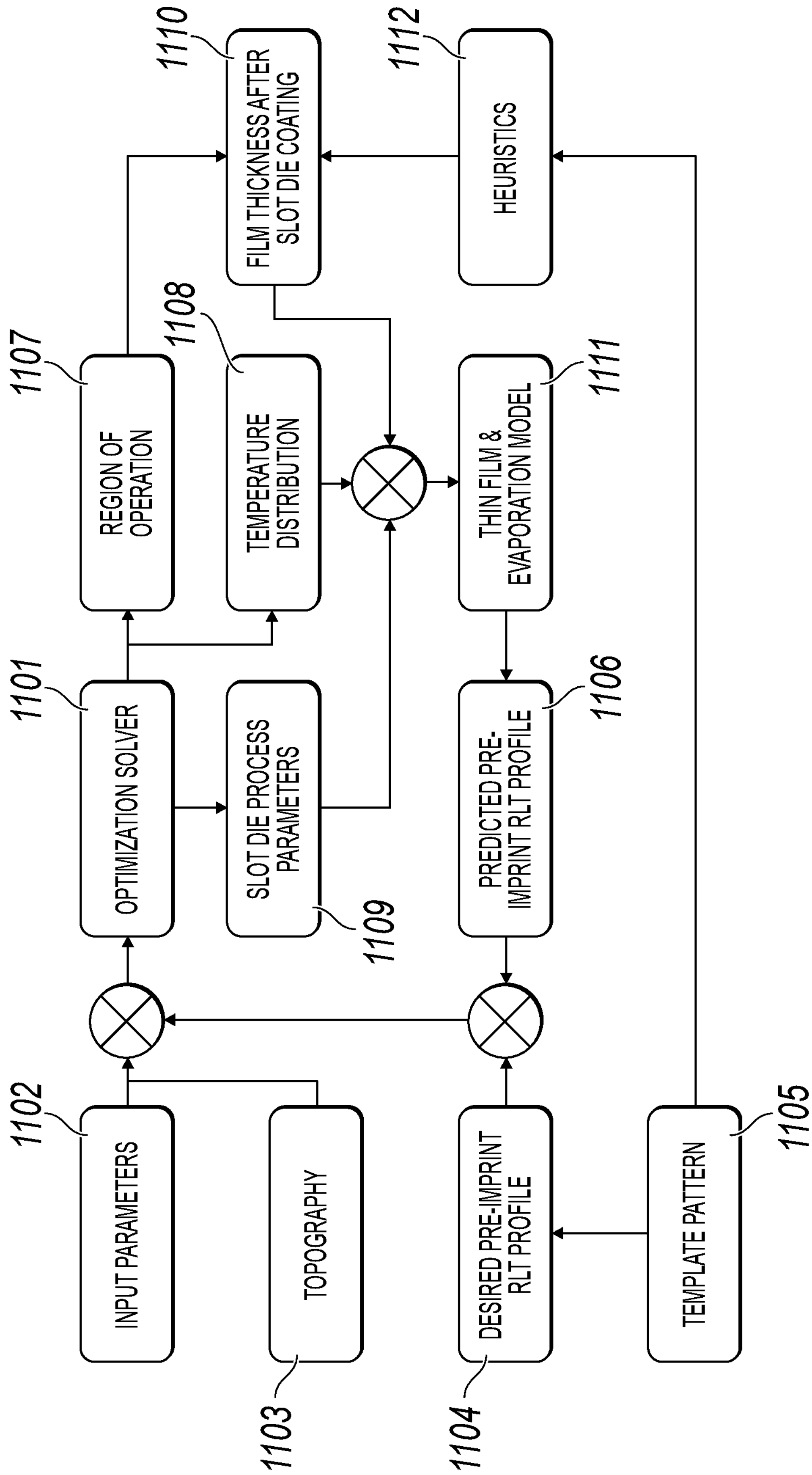


FIG. 11

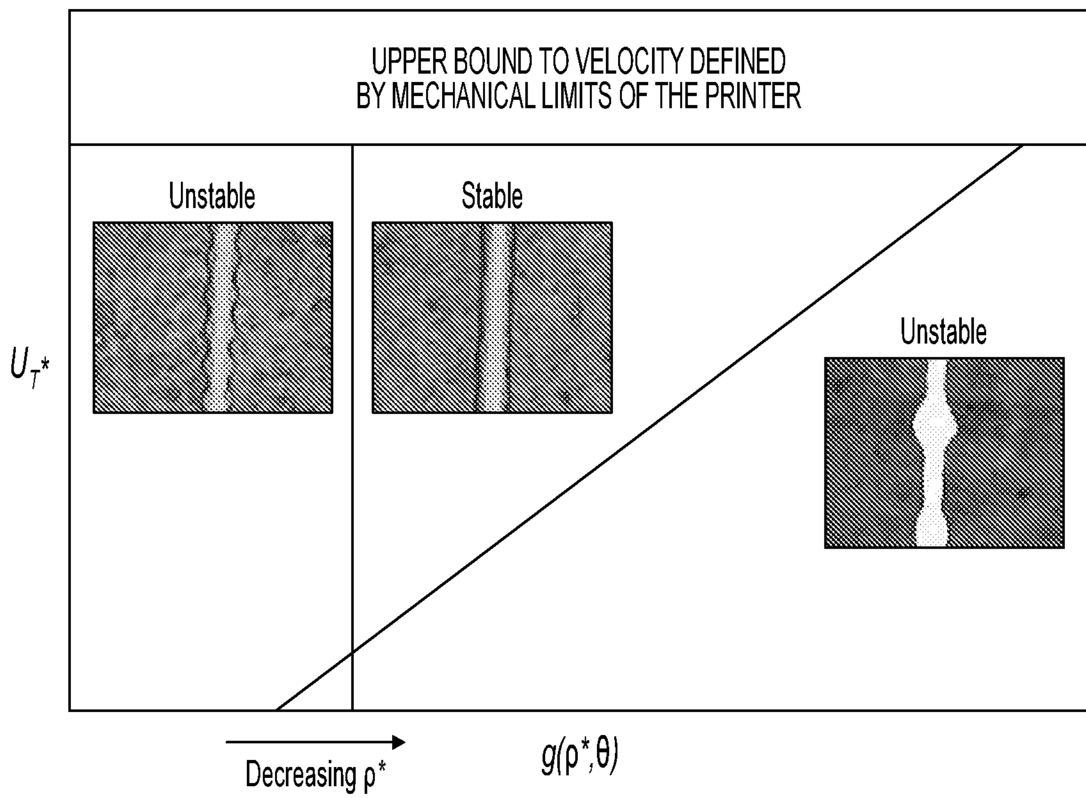
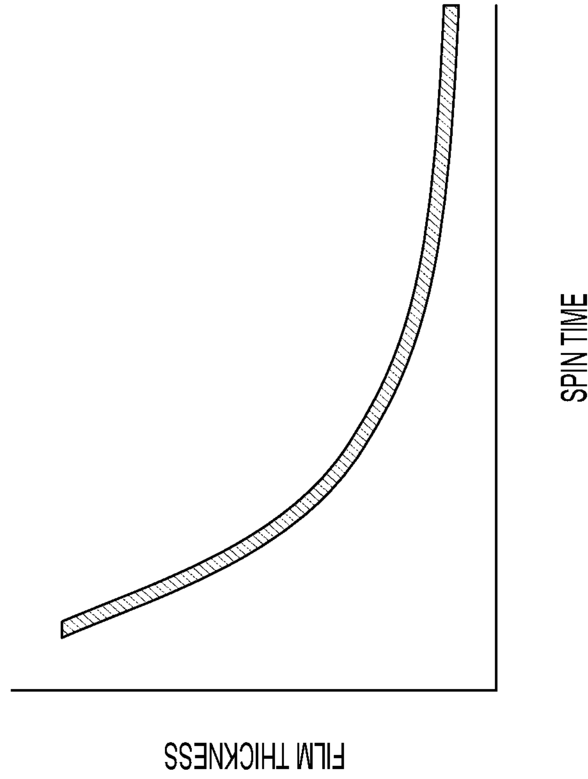


FIG. 12



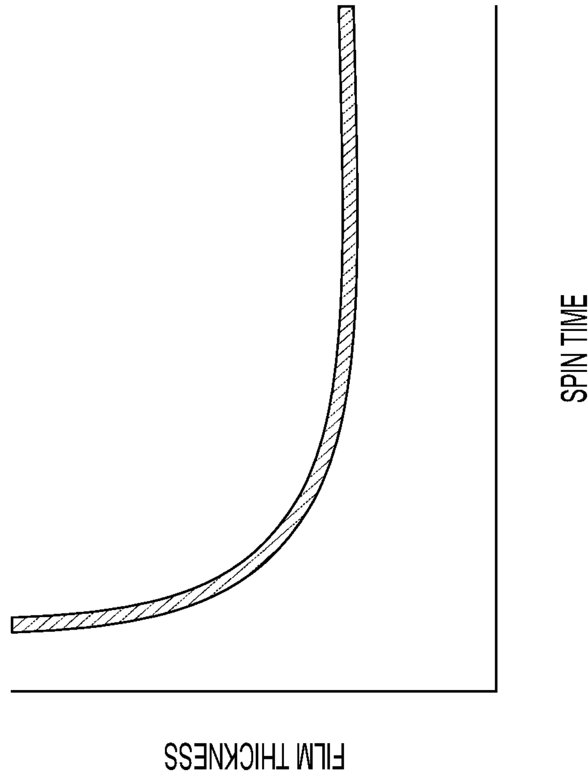
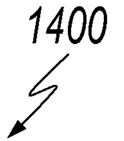


FIG. 13



PATTERN RESIST ON A SUBSTRATE (1401)

PERFORM A SHORT DESCUM ASH TO EXPOSE SUBSTRATE (1402)

SLOT-DIE COAT SUBSTRATE WITH TiO_2 OR, ALTERNATIVELY, DEPOSIT TiO_2 ON SUBSTRATE VIA CHEMICAL VAPOR DEPOSITION (1403)

PERFORM A BLANKET ETCH OF TiO_2 (1404)

FIG. 14

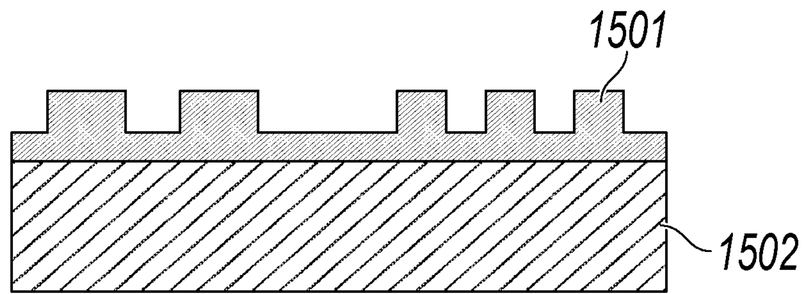


FIG. 15A

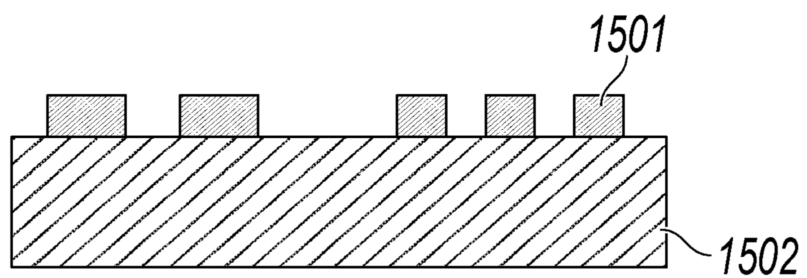


FIG. 15B

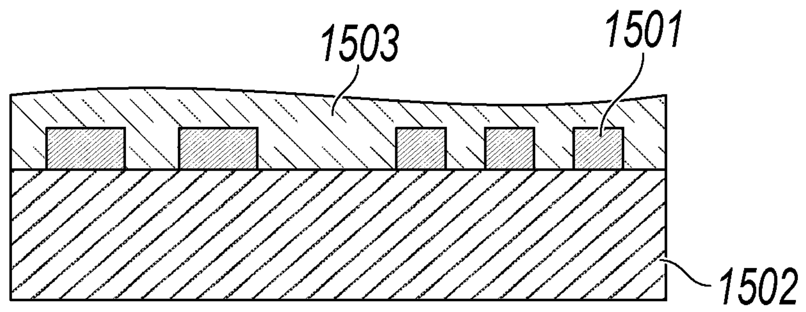


FIG. 15C

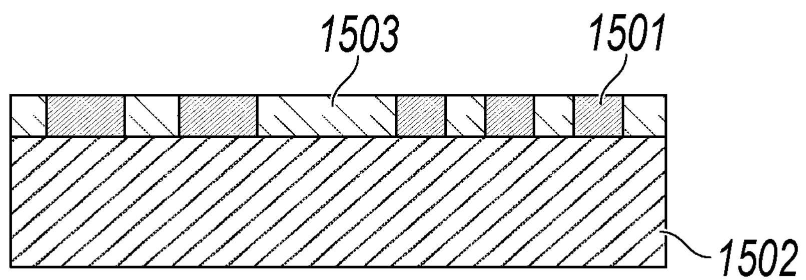


FIG. 15D

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2017/045373

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - B05D 1/02; B05D 1/26; B05D 1/34; B05D 1/40; B29C 45/76; B29C 59/02; B29C 59/16 (2017.01)
CPC - B05D 1/02; B05D 3/067; B05D 3/12; G01N 21/03; G01N 2201/02; G01N 2201/06113; G03F 7/0002; G03F 9/7088; H01L 21/027 (2017.08)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 250/548; 257/288; 257/390; 264/293; 264/406; 427/256; 427/258; 427/294; 427/359 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2015/0048050 A1 (BOARD OF REGENTS, THE UNIVERSITY OF TEXAS SYSTEM) 19 February 2015 (19.02.2015) entire document	1-50
Y	US 2010/0098940 A1 (LIU et al) 22 April 2010 (22.04.2010) entire document	1-50
Y	US 2005/0276919 A1 (TRUSKETT et al) 15 December 2005 (15.12.2005) entire document	2-5
Y	US 2010/0102487 A1 (SCHUMAKER et al) 29 April 2010 (29.04.2010) entire document	4, 28
Y	US 2010/0109205 A1 (FLETCHER et al) 06 May 2010 (06.05.2010) entire document	5, 26-29
Y	US 2011/0183521 A1 (SCHMID et al) 28 July 2011 (28.07.2011) entire document	9, 10, 38
Y	US 2008/0308971 A1 (LIU et al) 18 December 2008 (18.12.2008) entire document	13-17, 41-45
Y	US 2006/0062867 A1 (CHOI et al) 23 March 2006 (23.03.2006) entire document	21-23
Y	US 2013/0214452 A1 (CHOI et al) 22 August 2013 (22.08.2013) entire document	24
Y	US 2009/0214689 A1 (BAILEY et al) 27 August 2009 (27.08.2009) entire document	46, 47
A	US 2014/0027633 A1 (KUWABARA) 30 January 2014 (30.01.2014) entire document	1-50

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 November 2017	22 NOV 2017

Name and mailing address of the ISA/US	Authorized officer
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, VA 22313-1450 Facsimile No. 571-273-8300	Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2017/045373

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:
See extra sheet(s).

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-50

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

Continued from Box No. III Observations where unity of invention is lacking

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I, claims 1-50, drawn to fabricating patterns on rigid wafer substrates.
Group II, claims 51-52, drawn to a method for performing in-situ metrology on an area of a flexible substrate.

The inventions listed as Groups I-II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: the special technical feature of the Group I invention: implementing an inverse optimization scheme to determine process parameters used to obtain a desired film thickness of a liquid resist formulation, wherein said liquid resist formulation comprises a solvent and one or more non-solvent components as claimed therein is not present in the invention of Group II. The special technical feature of the Group II invention: determining an optimum positioning of said array of AFM tips on a wafer with a pattern, a topography variation or a variation in a film thickness, wherein each AFM tip in said array of AFM tips provides data that is aggregated to infer said pattern, said topography variation or said film thickness variation; scanning said wafer to measure said pattern, said topography variation or said film thickness variation; and aggregating and analyzing said measured pattern, said measured topography variation or said measured film thickness variation to infer said pattern, said topography variation or said film thickness variation as claimed therein is not present in the invention of Group I.

Groups I and II lack unity of invention because even though the inventions of these groups require the technical feature of measured film thickness, this technical feature is not a special technical feature as it does not make a contribution over the prior art.

Specifically, US 2014/0027633 A1 (KUWABARA) 30 January 2014 (30.01.2014) teaches measured film thickness (Paras. 14-15).

Since none of the special technical features of the Group I or II inventions are found in more than one of the inventions, unity of invention is lacking.