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(54) DEPOSITION TECHNIQUE TO PLANARIZE A MULTI-LAYER STRUCTURE

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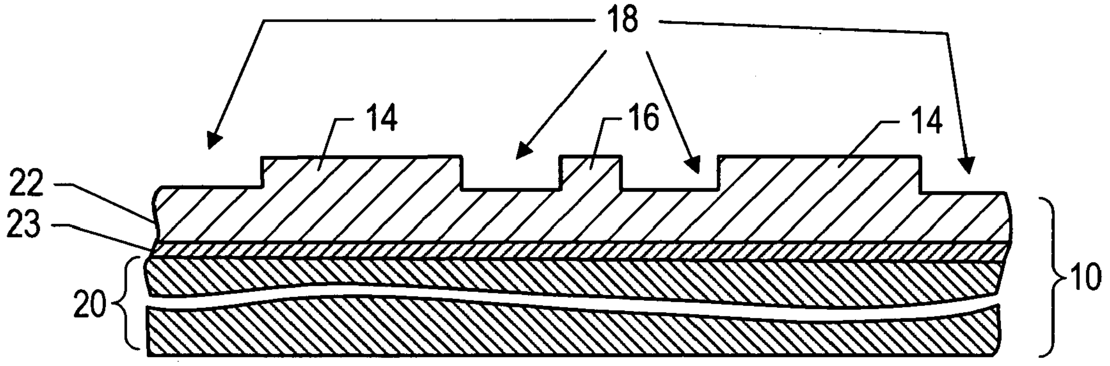
(57) ABSTRACT

The present invention is directed to a method of coating a substrate having a solidified layer formed thereon, that features depositing a flowable material upon the solidified layer and forming an additional layer having a smooth flowable surface upon the substrate by imparting rotational movement upon the substrate followed by leveling of the flowable material in an absence of the rotational movement. After the additional layer is formed, the same is solidified.



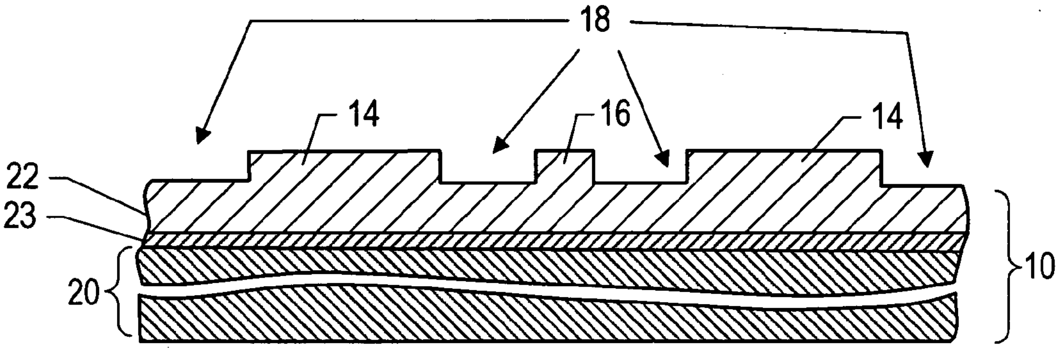


FIG. 1

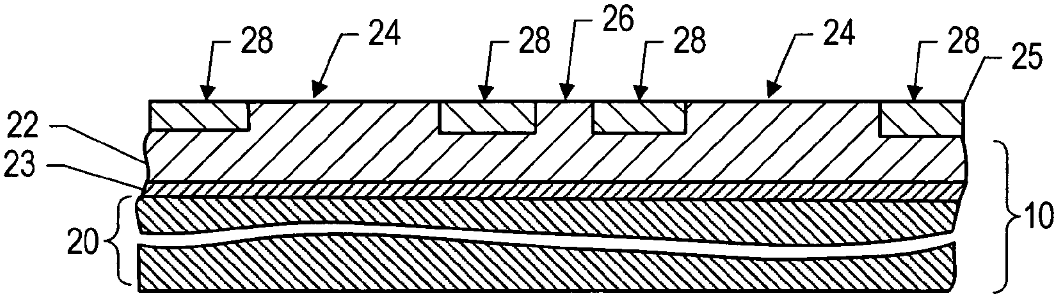


FIG. 2

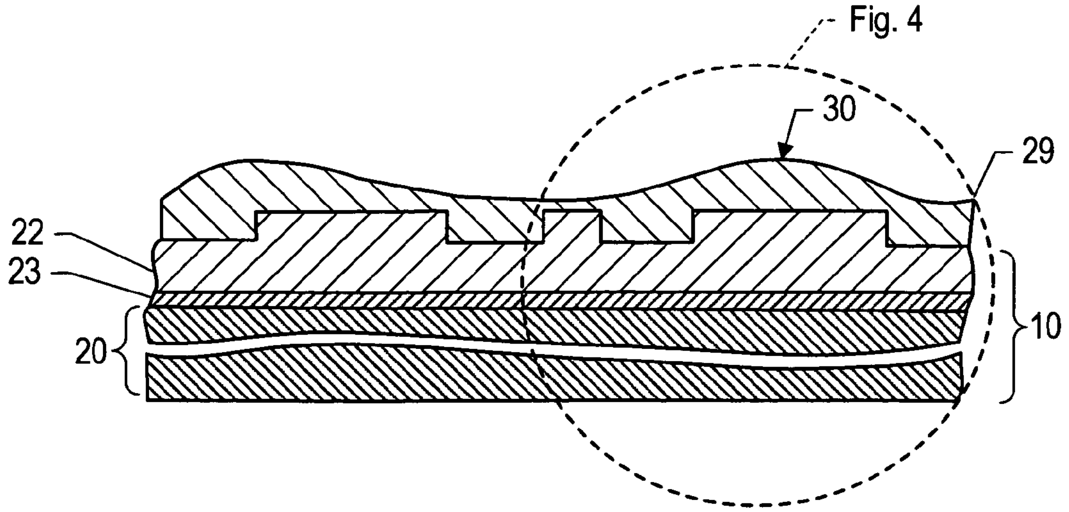


FIG. 3

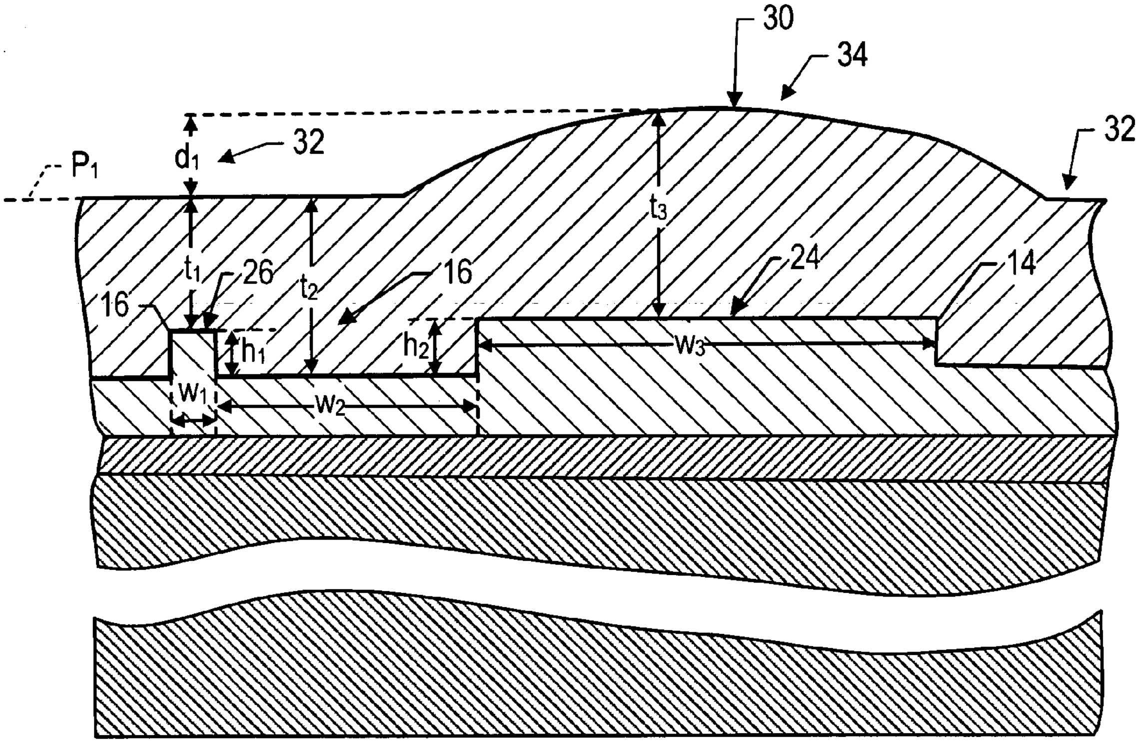


FIG. 4

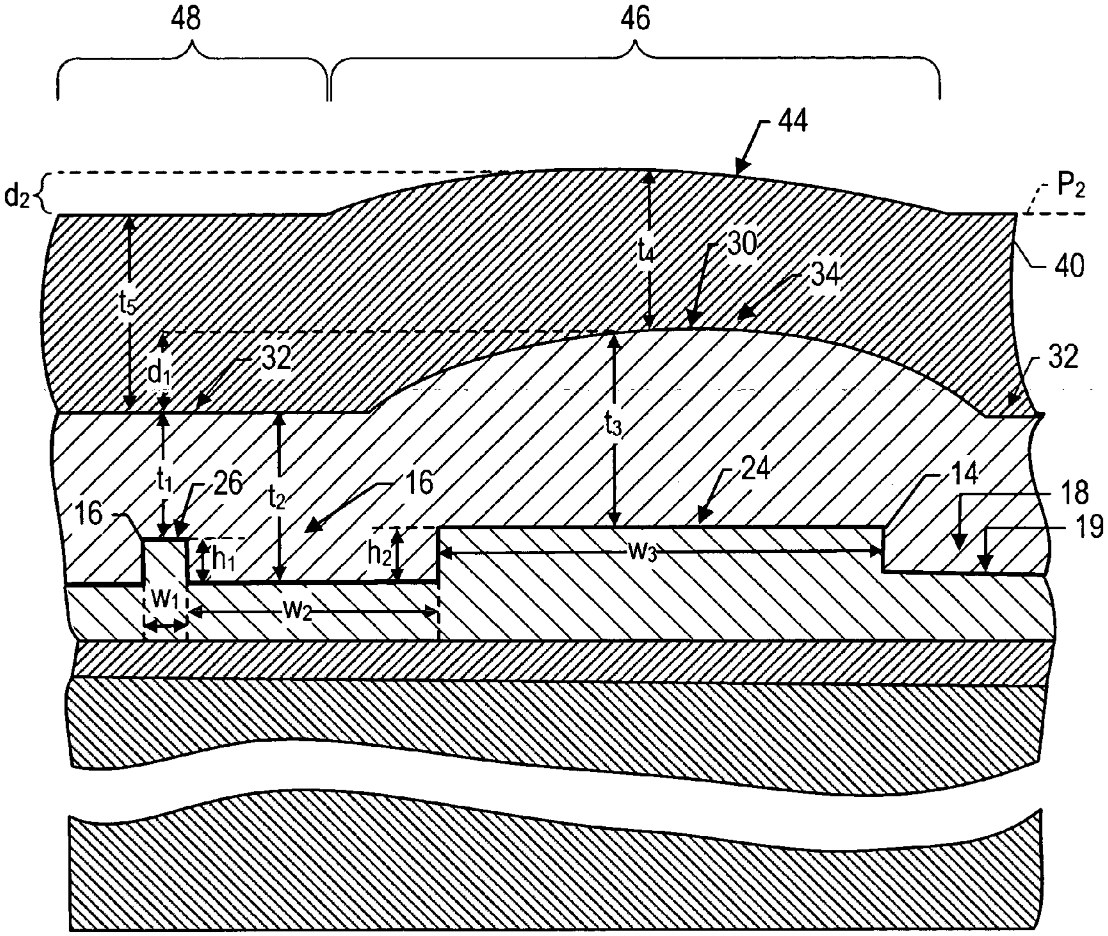

48
46
44
d2
P2
40
t5
t4
30
34
d1
32
32
t3
t1
26
t2
16
24
14
18
19
16
h1
h2
w3
w1
w2

FIG. 5

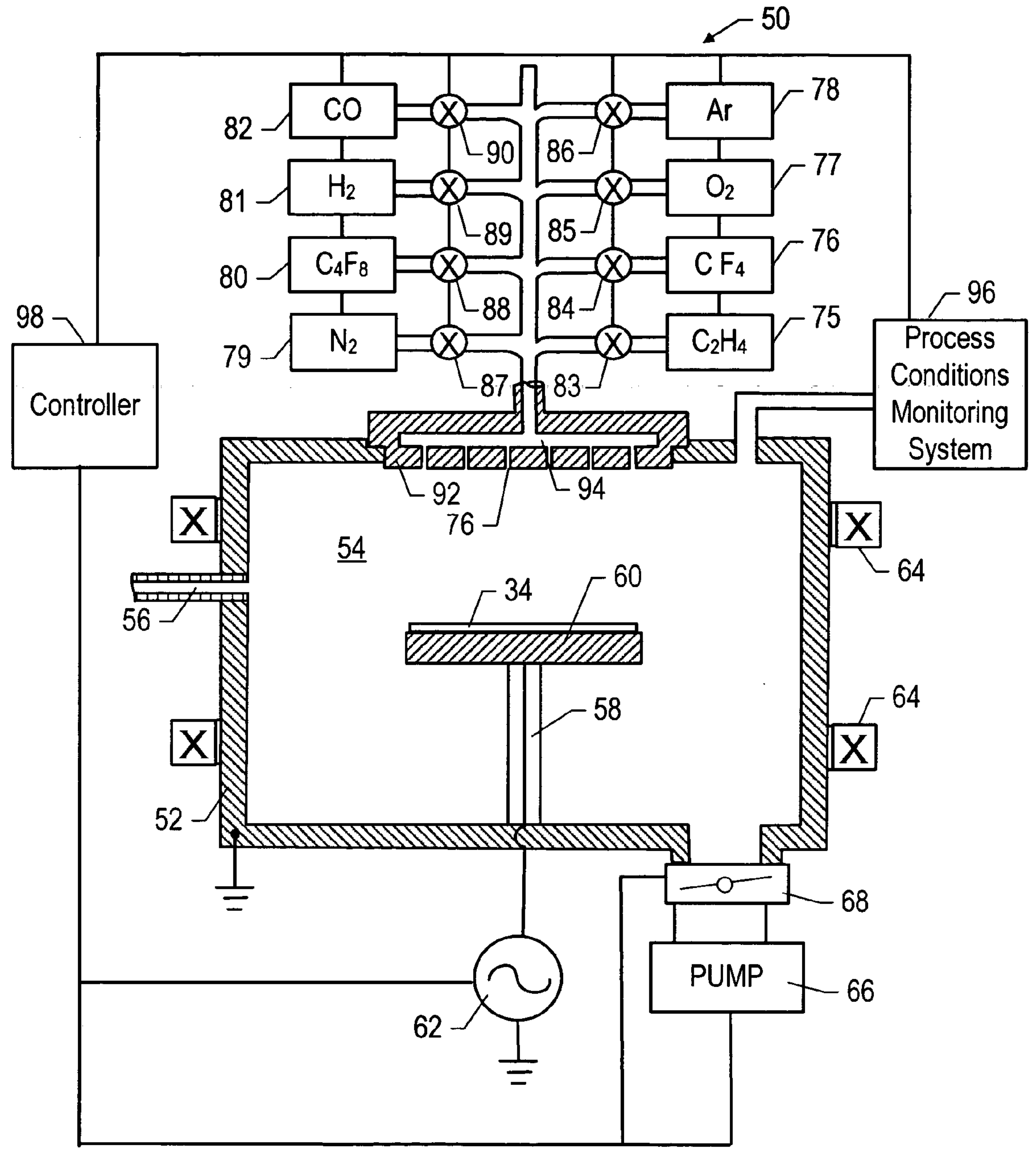


FIG. 6
(Prior Art)

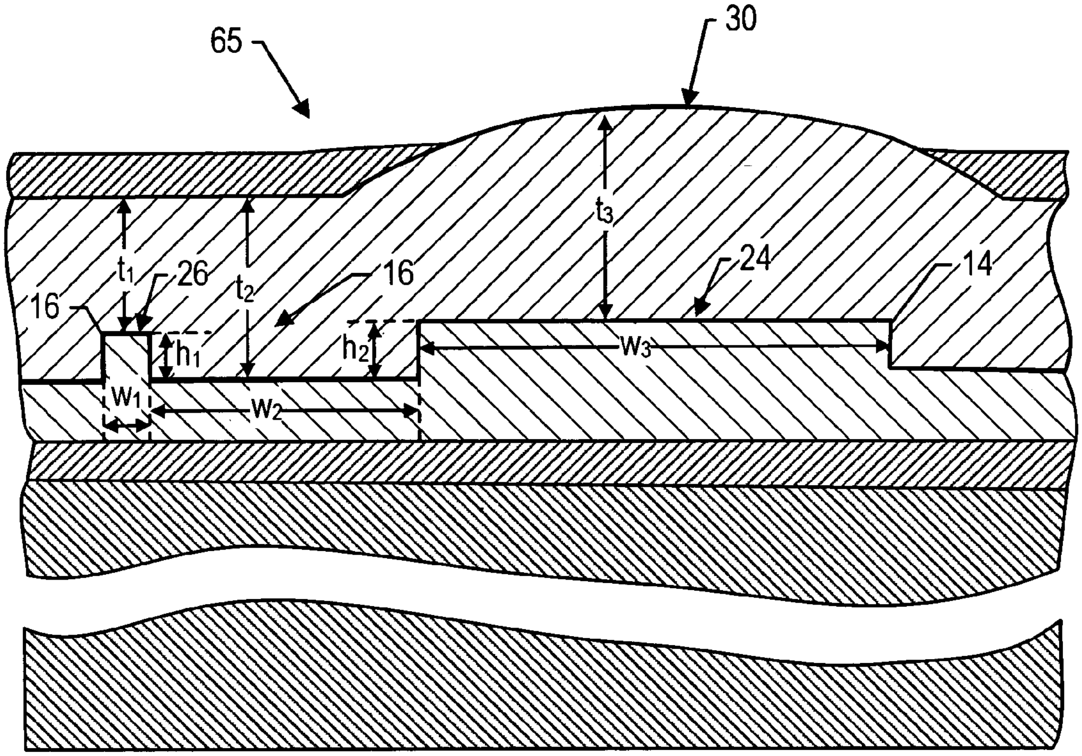


FIG. 7

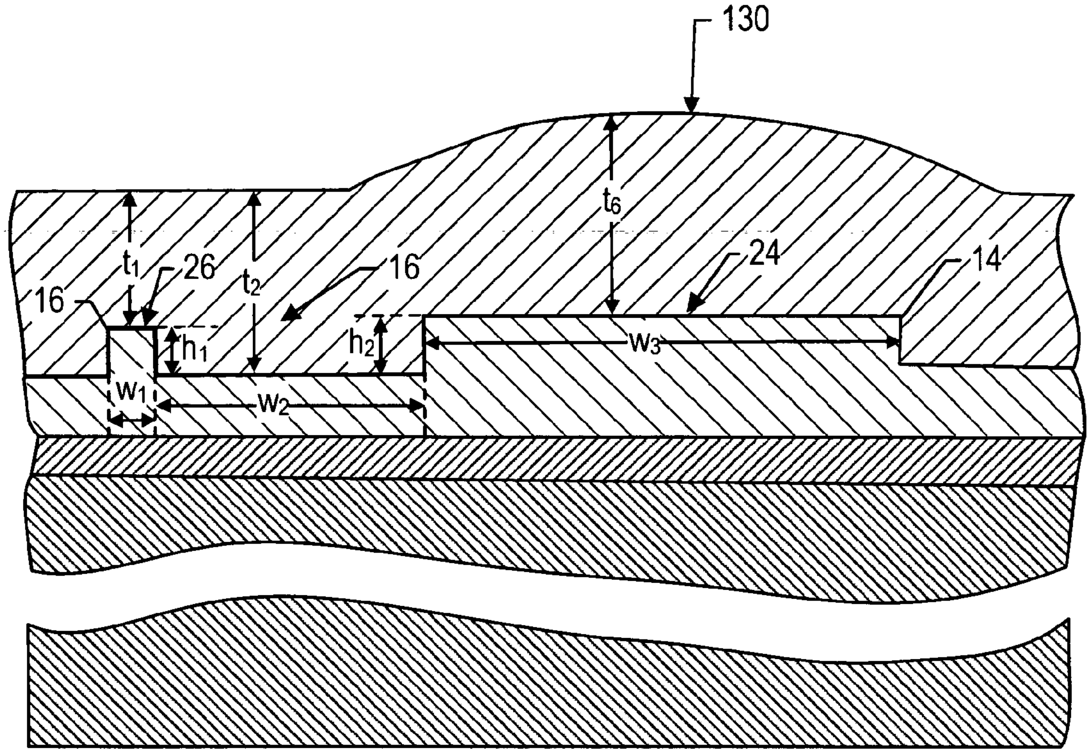


FIG. 8

DEPOSITION TECHNIQUE TO PLANARIZE A MULTI-LAYER STRUCTURE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application is a divisional of U.S. patent application Ser. No. xx/xxx,xxx (Attorney Docket No. P234M1D238) filed herewith, entitled ETCHING TECHNIQUE TO PLANARIZE A MULTI-LAYER STRUCTURE, listing David C. Wang and Frank Y. Xu as inventors, which application is incorporated by reference herein.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] The United States government has a paid-up license in this invention and the right in limited circumstance to require the patent owner to license other on reasonable terms as provided by the terms 70NANB4H3012 awarded by the National Institute of Standards and Technology (NIST).

BACKGROUND OF THE INVENTION

[0003] This invention relates to spin-on coating of substrates. Specifically, the present invention is directed to a method to coat a substrate employing spin-on techniques in furtherance of lithographic patterning.

[0004] Spin-coating is a well known technique employed to form a layer of material upon a substrate. Often the material is deposited upon a surface having anisotropic topography in furtherance of producing a film having a planar surface disposed opposite to the substrate surface. The planarity of the material surface is highly desirable for several processes, e.g., deposition of resist material in furtherance of patterning. As a result, studies have been undertaken to understand the behavior of films formed during spin-coating. Peurrung and Graves in Film *Thickness Profiles over Topography in Spin Coating*, Journal of the Electrochemical Society, Vol. 138 No. 7 (1991), set forth a theoretical analysis of spin-coating wet films over anisotropic surfaces. Peurrung and Graves conclude that the presence of anisotropicity of the substrate surface makes problematic production of a planar material surface. Many attempts have been undertaken to obtain a planar material surface from material spin-coated on an anisotropic surface.

[0005] U.S. Pat. No. 4,038,110 discloses a technique to planarize an anisotropic substrate surface involves forming a photoresist pattern in registration that with a pattern of unelevated areas present on the substrate. The photoresist pattern has narrower lateral dimensions than an elevated pattern whereby registration is facilitated. The photoresist pattern is flowed to laterally expand the photoresist and mask the unelevated areas.

[0006] In U.S. Pat. No. 4,741,926, one manner in which to overcome the drawbacks with multi-layer resists involve spreading a resin material over an anisotropic surface employing a dual spin cycle. The resin material is spread at a speed of approximately of not less than 4000 revolutions per minute (rpm), preferably from 6000 to 8000 rpm, until build-up of the coating is detectable on a side wall of a topographical feature facing the centrifugal center of the spinning substrate. The spin speed is immediately reduced to less than 4000 rpm, preferably from about 1000 to 3500 rpm, and spinning is continued for a time sufficient to dry the coating.

[0007] U.S. Pat. No. 4,794,021 discloses a method of forming a planarized layer on a substrate by spin coating a polymer over the substrate. Before the layer dries the substrate is heated in a pressure-controlled environment to control solvent loss while maintaining the polymer in a liquid-state. After a predetermined interval of time, the substrate is cured in a standard convention bake oven.

[0008] U.S. Pat. No. 5,736,424 discloses a method that includes contacting a material having a predetermined viscosity with an object having a flat surface. The material has a viscosity less than 1000 cp, and a flat surface is placed into contact with the material in such a manner that the material is planarized to a desired degree. The material is cured while in contact with the flat surface. The object is then separated from the material. The planarity of the planarizing material is then transferred into the underlying layer using conventional techniques.

[0009] U.S. Pat. No. 5,893,750 discloses a method of forming a planarized interlevel dielectric layer over interconnects formed upon a frontside surface of an upper topography of a silicon wafer. An anisotropic silicon dioxide (oxide) layer is first deposited over the interconnects. A spin-on glass (SOG) layer is then formed over the anisotropic oxide layer. The liquid SOG material flows over the upper surface, filling narrow spaces without creating voids and producing a surface smoothing effect at isolated vertical edges. After curing of the SOG layer, a chemical-mechanical polishing (CMP) process is applied to the frontside surface. The CMP process increases the planarity of the frontside surface by reducing surface heights of elevated features more so than surface heights in recessed areas. A need exists, however, to provide improved planarization techniques.

SUMMARY OF THE INVENTION

[0010] The present invention is directed to a method of coating a substrate having a solidified layer formed thereon, that features depositing a flowable material upon the solidified layer and forming an additional layer having a smooth flowable surface upon the substrate by imparting rotational movement upon the substrate followed by leveling of the flowable material in an absence of the rotational movement. After the additional layer is formed, the same is solidified. These and other embodiments are discussed more fully below.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. **1** is a cross-sectional view of a substrate having an anisotropic surface that is to be planarized in accordance with the present invention;

[0012] FIG. **2** is a cross-sectional view of the substrate shown in FIG. **1** having a planarized surface, in accordance with the present invention;

[0013] FIG. **3** is a cross-sectional view of the substrate shown in FIG. **1** having a semi-conformal layer deposited therein;

[0014] FIG. **4** is a detailed cross-sectional view of a region of the substrate shown in FIG. **3**;

[0015] FIG. **5** is a cross-sectional view of the substrate shown in FIG. **4** having a smoothing layer deposited thereon;

[0016] FIG. 6 is a cross-sectional view of a prior art etching chamber;

[0017] FIG. 7 is a cross-sectional view of substrate shown in FIG. 5 after being etched employing first etch conditions in accordance with the present invention;

[0018] FIG. 8 is a cross-sectional view of substrate shown in FIG. 7 after being etched employing second etch conditions in accordance with the present invention;

DETAILED DESCRIPTION OF THE INVENTION

[0019] Referring to FIG. 1, in certain patterning processes it is desired to form a planar surface upon substrates, such as substrate **10**, having an anisotropic surface. The anisotropic surface may include spaced-apart projections **14** and **16**, defining spaced-apart recessions **18**, which may result from any known previous patterning process. Projections **14** may be metal lines, photoresist, monocrystalline silicon and the like. In the present example, substrate **10** is discussed as including a wafer **20** formed from standard materials, e.g., mono-crystalline silicon. Present upon wafer **20** is a patterned layer **22** in which projections **14** and **16** are formed. In the present example it is desired to form a planarized surface, referred to as a crown surface **25**, in which substantially the entire surface area of an apex surface **24** of projections **14** and substantially the entire surface area of an apex surface **26** of projections **16** are exposed and coplanar with a surface **28** of a material deposited to fill recessions **18**. To that end, in an exemplary embodiment, patterned layer **22** is formed from a solidified polymeric material employing imprint lithography techniques, with a primer layer **23** being disposed between patterned layer and wafer **20**. Primer layer **23** is typically formed from spin-coating a layer of DUV30J-16. DUV30J-16 is a bottom anti-reflective coating, BARC, available from Brewer Science in Rolla, Mo. An exemplary bulk material from which to form patterned layer **22** is as follows:

Patterned Layer Bulk Imprinting Material

Isobornyl Acrylate

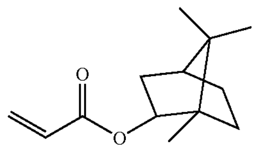
N-hexyl Acrylate

Ethylene Glycol Diacrylate

2-hydroxy-2-methyl-1-phenyl-propan-1-one

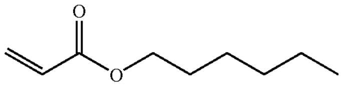
FS-2000

[0020] The acrylate component, isobornyl acrylate (IBOA), has the following structure:



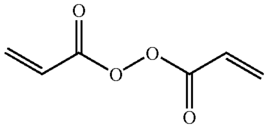
and comprises approximately 47% of bulk material by weight, but may be present in a range of 20% to 80%, inclusive. As a result, the mechanical properties of patterned layer **22** are primarily attributable to IBOA. An exemplary source for IBOA is Sartomer Company, Inc. of Exton, Pa. available under the product name SR 506.

[0021] The component n-hexyl acrylate (n-HA) has the following structure:



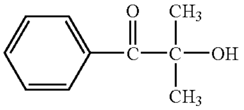
and comprises approximately 25% of bulk material by weight, but may be present in a range of 0% to 50%, inclusive. Also providing flexibility to patterned layer **22**, n-HA is employed to reduce the viscosity of the prior art bulk material so that bulk material, in the liquid phase, has a viscosity in a range of 2-9 Centipoises, inclusive. An exemplary source for the n-HA component is the Aldrich Chemical Company of Milwaukee, Wis.

[0022] A cross-linking component, ethylene glycol diacrylate, has the following structure:



and comprises approximately 25% of bulk material by weight, and may be present in a range of 10% to 50%, inclusive. EGDA also contributes to the modulus and stiffness buildup, as well as facilitates cross-linking of n-HA and IBOA during polymerization of the bulk material.

[0023] An initiator component, 2-hydroxy-2-methyl-1-phenyl-propan-1-one is available from Ciba Specialty Chemicals of Tarrytown, N.Y. under the tradename DAROCUR® 1173, and has the following structure:



and comprises approximately 3% of the bulk material by weight, and may be present in a range of 1% to 5%, inclusive. The actinic energy to which the initiator is responsive is broadband ultra-violet energy generated by a medium-pressure mercury lamp. In this manner, the initiator facilitates cross-linking and polymerization of the components of the bulk material. The component FS-2000 is a surfactant that provides preferential adhesion and release upon polymerization of the bulk material. FS-2000 is sold by Mason Chemical Company of Arlington Heights, Ill. under the product name MASURF® FS-2000 and comprises approximately 2% of the bulk material by weight, and may be present in a range of 0.1% to 5%, inclusive. An exemplary imprint lithography technique to deposit patterned layer **22** is disclosed in co-pending U.S. patent application Ser. No. 11/068,171, filed Feb. 28, 2005, entitled "Composition to Reduce Adhesion Between a Conformable Region and a Mold," having Frank Xu and Michael N. Miller listed as inventors, which is incorporated by reference herein.

[0024] In furtherance of forming crown surface **25**, projections **14** and **16** are covered, and recessions **18** filled, with a polymerizable material, referred to herein as a semi-conformal composition, which is applied by spin-coating to form semi-conformal layer **29**. In the present example, semi-conformal layer **29** is formed from a silicon-containing polyermizable material employing a Brewer Science Model CEE® 4000 spin-coating system. The polymerizable material is centrally disposed on substrate **10** before rotation occurs. After dispensing of the polymerizable material, substrate **10** is accelerated 3,000 revolutions per minute (rpm) per second to reach a maximum rotational velocity of approximately 1000 rpm. The maximum rotational velocity is maintained until substantially all of the solvent in the polymerizable material has been removed. This is detected optically by the unaided eye as the color of semi-conformal layer **29** remaining substantially unchanged during rotation of substrate **10**. Following removal of the solvent, substrate **10** is placed upon a heating device (not shown), such as a hot plate, to raise the temperature thereof, by conductive heating, to approximately 180° C. for 60 seconds.

[0025] An exemplary bulk material to include in the semi-conformal composition to form semi-conformal layer **29** is as follows:

Semi-Conformal Layer Bulk Material

Hydroxyl-Functional Polysiloxane

Hexamethoxymethylmelamine

Toluenesulfonic Acid

[0026] The hydroxyl-functional polysiloxane component is present in SEMI-CONFORMAL BULK MATERIAL in amounts of approximately 80% by weight of SEMI-CONFORMAL BULK MATERIAL, but may be present in a range of 40 to 95%, inclusive by weight, depending on the thicknesses desired for semi-conformal layer **29**. An exemplary hydroxyl-functional polysiloxane component used in the present invention is a silicon T-resin intermediate available from Dow Corning® (Midland, Mich.) under the tradename Z-6018.

[0027] The hexamethoxymethylmelamine(HMMM) is a cross-linking agent component is present in SEMI-CONFORMAL BULK MATERIAL in amounts of approximately 19% by weight of SEMI-CONFORMAL BULK MATERIAL, but may be present in a range of 10 to 30%, inclusive by weight. An exemplary HMMM component is available from Cytec Industries, Inc. (West Paterson, N.J.) under the tradename CYMEL 303ULF.

[0028] The toluenesulfonic acid component is a catalyst present in the SEMI-CONFORMAL LAYER BULK MATERIAL in an amount of component is present in SEMI-CONFORMAL BULK MATERIAL in amounts of approximately 1% by weight of SEMI-CONFORMAL BULK MATERIAL, but may be present in a range of 1 to 2%, inclusive by weight. An exemplary catalyst is available from Cytec Industries, Inc. (West Paterson, N.J.) under the tradename CYCAT 4040.

[0029] Typically, the SEMI-CONFORMAL LAYER BULK MATERIAL is employed with a solvent to form the semi-conformal composition employed to form semi-conformal layer **29**. The solvent may be present in the semi-conformal composition in amounts of approximately 60% to 98% by weight, dependent upon the desired thicknesses of semi-conformal layer **29**, with the remaining portions of the semi-conformal composition being the SEMI-CONFORMAL LAYER BULK MATERIAL **58**. An example of a solvent used in the present invention is methyl amyl ketone available from Aldrich Co. (St. Louis, Mo.) under the tradename MAK.

[0030] The anisotropy of surface of substrate **10** causes thickness variations in semi-conformal layer **29** that present as troughs **32** and hills **34**. It was observed that regions of a surface **30** of semi-conformal layer **29** in superimposition with projection **16** and recession **18** had a substantially smooth, if not planar surface, because projection 16 has small lateral dimension, w_1. This results in a thickness t_1, of semi-conformal layer **29**, measured between surface **30** and apex surface **26** of projection 16, being substantially equal to thickness t_2-h_1, with h_1 being the height of projection **16**. This was observed for projections, such as projection **16**, having a width, w_1, of several microns or less, which is smaller than width, w_2, of recession **18**. Projections, such as projection **14**, having a width, w_3, which is tens of microns or larger, were observed to produce hills, such as hill **34**. Hill **34** is defined by a region of semi-conformal layer **29** having a varying thickness measured with respect to apex surface **24** of projection **14** and surface **30**. The maximum thickness, t_3, of the region of semi-conformal layer **29** in superimposition with projection **14**, is approximately equal to thickness t_2. The portion of surface **30** associated with the maximum thickness of hill **34** is spaced-apart from a plane P_1 in which the remaining regions of surface **30** lie, a distance d_1. Typically, d_1 is approximately equal to height, h_2, of projection **14**. As a result, a blanket etch to expose the entire area of apex surface **30** and hill **34** would result in projection **16** being lost (removed through the etching process) due to the presence of hill **34** in furtherance of forming crown surface **25**. This is undesirable.

[0031] Referring to both FIGS. **2**, **4** and **5**, to minimize, if not prevent, the portion of projection **16** that is removed upon exposure of the entire area of apex surface **34**, an additional layer, referred to as smoothing layer **40**, is disposed upon surface **30**. Smoothing layer **40** functions to further reduce non-planarity perturbations in surface **30** due, for example, to troughs **32** and hills **34**. To that end, smoothing layer **40** is typically disposed on surface **30** employing spin-on techniques to minimize the time required to form the same. As a result, the material from which smoothing layer **40** is formed includes a solvent. It is desired to form smoothing layer **40** from a material that maintains a fluidic state after spin-on coating has effectively removed substantially all of the solvent present therein. This minimizes non-planarity perturbations present in a smoothing surface **44** resulting from smoothing layer **40** after formation thereof by maximizing leveling of smoothing surface **44** in the absence of centrifugal forces. This is based upon the realization that conformal coating dominates in the presence of centrifugal forces and planarization dominates in the presence of capillary forces. A ratio of centrifugal force (F_c) to capillary force (F_p) is proportional to the cubic of feature lateral dimension, (w) that may be expressed as follows:

$$F_c/F_p \alpha W^3 \quad 1)$$

To avoid the deleterious effects of centrifugal forces, the material from which smoothing layer **40** is formed maintains a fluidic state after spin-on coating has effectively removed substantially all of the solvent present therein.

[**0032**] An exemplary bulk material from which to form smoothing layer **40** is as follows:

Smoothing Layer Bulk Material 1

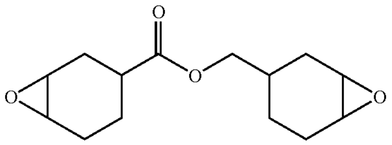
Cycloaliphatic Epoxy

ω-Caprolactone Triol

Photoinitiator

Fluorosurfactant

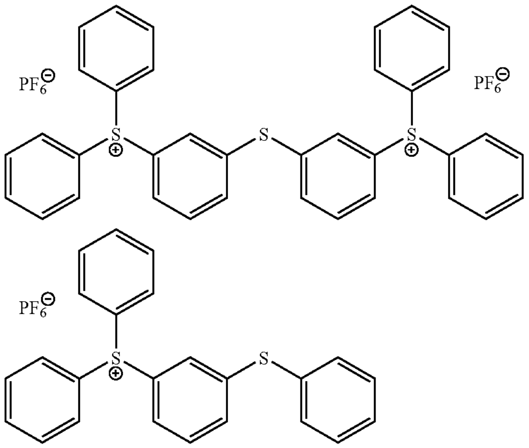
[**0033**] The cycloaliphatic epoxy component has the following structure:



The cycloaliphatic epoxy component comprises approximately 87% of bulk material by weight. As a result, the mechanical properties of smoothing layer **40** are primarily attributable to the cycloaliphatic epoxy component. An exemplary source of the cycloaliphatic epoxy component is sold by Dow Chemical Company of Midland, Mich. as chemical name 3,4-epoxycyclohexylmethyl-3,4-epoxycyclohexane carboxylate and sold under the tradename ERL-4221LV.

[**0034**] The ω-caprolactone triol component comprises approximately 10% of the bulk material by weight. This component increased the catioinic curing speed of SMOOTHING LAYER BULK MATERIAL 1. An exemplary source of the ω-caprolactone triol component is sold by Dow Chemical Company of Midland, Mich. under the tradename Tone 0301.

[**0035**] The photoinitiator component comprises approximately 3% of the bulk material by weight and facilitates cross-linking and polymerization of the remaining components of bulk material in response to actinic energy. An exemplary photoinitiator is a cationic photoinitiator comprising a mixture of triarylsulfonium hexafluorophosphate salts in a propylene carbonate. An exemplary source of the photoinitiator component has the following structure:



and is sold by Dow Chemical Company of Midland, Mich. under the tradename UVI 6992.

[**0036**] The fluorosurfactant component is a nonionic fluorinated acrylic copolymer based surfactant that comprises less than 1% of the bulk material by weight. An exemplary fluorosurfactant is available from Dainippon Ink & Chemical of Japan under the tradename MegaFace™ R-08.

[**0037**] Typically, the SMOOTHING LAYER BULK MATERIAL is employed with a solvent to form a smoothing composition employed to form smoothing layer **40**. The solvent may be present in the smoothing composition in amounts of approximately 20% to 98% by weight, dependent upon the desired thicknesses of smoothing layer **40**, with the remaining portions of the semi-conformal composition being the SMOOTHING LAYER BULK MATERIAL. An example of a solvent used in the present invention is methyl amyl ketone available from Aldrich Co. (St. Louis, Mo.) under the tradename MAK.

[**0038**] Surface **30** is coated with the smoothing composition by spin-on techniques employing a Brewer Science Model CEE® 4000 spin-coating system to form smoothing layer **40**. The smoothing composition is centrally disposed on surface **30** before rotation occurs. After dispensing of the smoothing composition, substrate **10** is accelerated 5,000 revolutions per minute (rpm)/s to reach a maximum rotational velocity of approximately 4000 rpm. The maximum rotational velocity is maintained until substantially all of the solvent in the polymerizable composition has been removed. This is detected optically by the unaided eye as the color of semi-conformal layer **29** remaining substantially unchanged during rotation of substrate **10**. Thereafter, rotation of substrate **10** is ceased and leveling of smoothing surface **44** is allowed to occur in the absence of movement of substrate **10**. Typically, leveling occurs for 2-30 minutes and at ambient atmospheric conditions, i.e. ambient temperatures and pressures. Exemplary ambient temperatures and pressures are 25° Celsius and 760 Torr, respectively. After the desired leveling time has occurred, smoothing layer is exposed to broadband ultraviolet energy for approximately 120 seconds with a lamp intensity of 20 mW/cm^2 to polymerize and cross-link the smoothing composition. This is typically achieved employing a light source sold by OAI of San Jose, Calif. as Model 30 LS that may produce an 8 inch uniform beam.

[**0039**] Hill **34** causes regions **46** of smoothing surface **44** to have a varying thickness measured with respect to surface **30**. The thickness, t_4, differs from a thickness, t_5, of regions **48** of smoothing layer **40** outside of region **46**. This results in the portion of surface **44** associated with the maximum thickness of region **46** being spaced-apart from a plane, P_2, in which the remaining regions of surface **46** lie, a distance d_2. The bulk material from which smoothing layer **40** is fabricated facilitates, for a given deposition process, to ensure that thickness, t_4, is less than thickness, t_5; hence, d_1 is greater than d_2. This effectively reduces the thickness offset between exposed surfaces, in this case smoothing surface **44** and both, nadir surface **19** of recession **18**, and apex surface **24**.

[**0040**] Assuming smoothing layer **40** and semi-conformal layer **29** have substantially similar etch characteristics, e.g., etch rate, for a given etch recipe, or groups of etch recipes, the presence of smoothing layer **40** reduces the magnitude of over-etch to which the projection **16** is subject to when exposing apex surface **24**. The reduction would be the absolute value of the difference between d_1 and d_2. For example, assuming height h_2 is 100 nanometers (nm), d_1 would be approximately 100 nm. It was found that depositing smoothing layer **40** with a thickness, t_5, being approximately 500 nm, provided thickness, t_4, of approximately 440 nm. As a result, d_2 is approximately 60 nm. This amounts to a 60% improvement of the degree of planarization (DOP). In the absence of smoothing layer **40**, the DOP may be defined as follows:

$$\mathrm{DOP}=(t_2-t_3)/h_2\times 100\% \qquad 2)$$

with t_2, t_3 and h_2 shown in FIG. **5**. With the presence of smoothing layer **40**, the DOP may be defined as follows:

$$\mathrm{DOP}=[t_2+(d_1-d_2)-t_3]/h_2\times 100\% \qquad 3)$$

Assuming projection **16** has a height, h_1, of 100 nm, the presence of smoothing layer **40** would result in projection **16** having a height, h_1, of approximately 60 nm upon exposure of surface **34**.

[**0041**] Further planarization benefit may be obtained by taking advantage of etch rate differential provided by differing etch recipes. For example, assuming that semi-conformal layer **29** had an etch rate, for a given etch recipe, that was 20% faster than the associated etch rate of smoothing layer **40**, it may be seen that the reduction in height, h_1, may be further reduced increased by 12 nm, i.e., height h_1 of projection **16** is approximately 72 nm upon exposure of the entire area of surface **34**. This may be desirable. Conversely, were the etch rate associated with semi-conformal layer **29**, for a given etch recipe, 20% slower that the associated etch rate of smoothing layer **40**, the planarization benefits of smoothing layer may be reduced. The height, h_1, of projection **16** would be reduced by 12 nm so that h_1 would be reduced to 48 nm upon exposure of the entire surface **34**.

[**0042**] Referring to FIGS. **5** and **6**, matching the etch characteristics of the materials of semi-conformal layer **29** and smoothing layer **40** may be problematic. As a result, an etch recipe has been developed that compensates for the etch rate differential presented by semi-conformal layer **29** and smoothing layer **40** SO that both etch at substantially the same rates. To that end, an etching system, such as a magnetically-enhanced reactive ion etching (MERIE) reactor **50** is employed. Reactor **50** includes grounded walls **52** defining a chamber **54** and slit valve opening **56** allowing ingress to and egress from chamber **54**. Disposed within chamber **54** is a cathode pedestal **58** with an electrostatic chuck **60** selectively clamping the wafer that may be coupled to a power source (not shown). Cathode pedestal **58** may include channels (not shown) through which coolant fluid (not shown), flows to facilitate control of the temperature of the chuck. An RF power supply **62** is in electrical communication with cathode pedestal **58** to facilitate control of the DC bias to chuck **40** and generation of a plasma within chamber **54**. A vacuum pump system **66** pumps the chamber **54** through an adjustable throttle valve **68**.

[**0043**] Processing gases are supplied from gas sources **75-82** through respective mass flow controllers **83-90** to a quartz gas distribution plate **92** positioned opposite to chuck **60**. The distribution plate **92** includes a manifold **94** receiving the processing gas and communicating with chamber **54** through a showerhead having a large number of distributed apertures **96** so as to inject a more uniform flow of processing gas into chamber **54**. During operation, pump **66** is operated to establish a pressure in chamber **54** that is approximately 30 milliTorr (mT). Mass flow controllers **84** and **85** are operated to establish a flow rate from supplies **76** and **77**, respectively. Specifically, supply **76** provides a flow of CF_4 gas into chamber **54** at approximately 90 standard cubic centimeters per minute (sccm). Supply **77** provides a flow of oxygen, O_2, gas into processing region at approximately 10 sccm. Power supply **62** is operated at 300 Watts. This configuration results in semi-conformal layer **29** and smoothing layer **40** etching at substantially the same rates, e.g., semi-conformal layer **29** etches at approximately 161.3 nm/minute±10 nm/minute, and smoothing layer **40** etches at approximately 167.4 nm/minute±10 nm/minute. It is desired to minimize the time required to complete etching, i.e., to expose surfaces **32** and **34**.

[**0044**] Referring to both FIGS. **6** and **7** to minimize the time required to complete etching, a sequential etch process is employed to maximize the etch rate of materials being etched while minimizing the etch rate differential among materials undergoing etch. The sequential etch process includes a first etch condition that minimizes the time required to remove portions of smoothing layer **40**. To that end, pump **66** operates to establish a pressure in chamber **54** that is approximately 40 mT. Mass flow controllers **83**, **85** and **87** are operated to establish a flow rate from supplies **75**, **77** and **79**, respectively. Specifically, supply **75** provides a flow of C_2H_4 gas into chamber **54** at approximately 40 sccm, and supply **77** provides a flow of oxygen, O_2, gas into chamber **54** at approximately 100 sccm. Supply **79** provides a flow of nitrogen, N_2, gas into chamber **54** at approximately 200 sccm. Supply **62** is operated at 500 Watts. These process conditions are maintained to form a multi-material semi-planar surface **65** that includes SEMI-CONFORMAL MATERIAL, resulting from the exposure of surface **30**, and the remaining regions of SMOOTHING LAYER MATERIAL. After forming semi-planar surface **65**, the etch process is terminated and the process conditions changed. Formation of semi-planar surface **65** may be determined from a priori knowledge in which the time required to expose the same is known and the process conditions are terminated after the required time had lapsed. To that end, a process conditions monitoring system **96** may be in communication with chamber **54** which is configured to measure performance of the etch process, e.g., measure an etch rate, an etch selectivity, an etch uniformity, feature profile angle, and critical dimension. System **96** may be an in-situ or ex-situ device. In the case of an in-situ device, system **96** includes a scatterometer (not shown), incorporating beam profile ellipsometry and beam profile reflectometry. The scatterometer (not shown) may be positioned within a transfer chamber (not shown). In the case of an ex-situ device, system **96** includes a scanning electron microscope (not shown).

[0045] Operation of reactor **50** is achieved by a controller **98** in data communication therewith to control the operations of the systems associated with reactor **50**. To that end, controller **98** is in data communication with RF supply **62**, pump **66**, throttle valve **68**, mass flow controllers **83-90**, supplies **75-82** and process condition monitoring system **96**. Controller **102** includes a microprocessor (not shown), memory (not shown), and a digital i/0 port (not shown) that is capable of generating control voltages sufficient to communicate with reactor **50**. A program stored in the memory (not shown) and selectively operated on by microprocessor controls the operation of reactor **50**.

[0046] The processing conditions in chamber **54** are established so that semi-conformal layer **29** and the remaining portions of smoothing layer **40** are etched at substantially the same rate. To that end, the chamber pressure is approximately 30 mT, power supply **62** is operated at 300 Watts and oxygen, O_2, gas is flowed into chamber at approximately 10 sccm and CF_4 gas is flowed into chamber **54** approximately 90 sccm. Upon removal of substantially all of the remaining portions of smoothing layer **40**, the DOP of 60% is maintained in a surface **130**, which is defined by the remaining portions of semi-conformal layer **29**. As a result the maximum thickness of t_6 of the remaining portion of hill **34** is less than thickness t_3. Specifically, thickness t_6 is defined substantially as follows:

$$t_6=t_3-(d_1-d_2). \qquad 3)$$

Thus, the smaller the value of d_2, the greater the degree of planarization in multi-material semi-planar surface **65** afforded by smoothing layer **40**.

[0047] Referring to FIGS. **2**, **6** and **8** following formation of surface **130**, etch conditions are changed to maximize the etch rate of the remaining portions of semi-conformal layer **29** while forming crown surface **25** and maximizing the planarity thereof. To that end, chamber **54** is pressurized to 50 mT, power supply **62** is operated at 500 Watts, and supply **75** provides C_4F_8 gas into chambers **54** at approximately 10 sccm. Supply **77** provides oxygen gas into chamber **54** at approximately 20 sccm, and supply **78** provides Argon gas into chamber **54** at approximately 100 sccm.

[0048] Following formation of crown surface **25**, patterned layer **22** may be etched establishing conditions in chamber **54** such that chamber pressure is 15 mT, power supply **62** is operated at 120 Watts and supply **82** introduces CO gas into chamber **54** at a rate of 100 sccm. Supply **77** introduces oxygen, O_2, gas into chamber **54** at a rate of approximately 20 sccm to take advantage of the etch differential provided by regions **24** and **28**, as discussed in U.S. patent application Ser. No. 10/789,319, filed Feb. 27, 2004, entitled, COMPOSITIONS FOR AN ETCHING MASK COMPRISING A SILICON-CONTAINING MATERIAL, having Frank Y. Xu, Michael N. Miller and Michael P. C. Watts listed as inventors, which is incorporated by reference herein.

[0049] The embodiments of the present invention described above are exemplary. Many changes and modifications may be made to the disclosure recited above while remaining within the scope of the invention. For example, in lieu of the SMOOTHING LAYER BULK MATERIAL DISCUSSED ABOVE, a T-structure silicone resin from Dow Corning Company, Midland, Mich. sold under the product name Z-6018 may be employed. In this manner Z-6018 would comprise 100% of the bulk material. The smoothing composition would comprise 20% Z-6018 and 80% of the methyl amyl ketone available from Aldrich Co. (St. Louis, Mo.) under the tradename MAK.

[0050] Employing the spin-coating system discussed above, the Z-6018 smoothing composition is centrally disposed on surface **30** before rotation occurs. After dispensing of the smoothing composition, substrate **10** is accelerated to 5,000 rpm/s to reach a maximum rotational velocity of approximately 2,500 rpm. The maximum rotational velocity is maintained until substantially all of the solvent in the polymerizable composition has been removed. This is detected optically by the unaided eye as the color of semi-conformal layer **29** remains substantially unchanged during rotation of substrate **10**. At these process conditions semi-conformal layer **29** is solidified and will not level. To achieve leveling of semi-conformal layer **29**, the substrate **10** is baked in an oven at 120° Celsius for fifteen minutes during which time semi-conformal layer **29** becomes fluidic, e.g., reflows, to facilitate leveling of smoothing surface **44**. Cooling is achieved by placing the same on an air-cooled cold plate having flows of ambient air directed toward substrate **10** for two minutes to solidify semi-conformal layer **29**.

[0051] The scope of the invention should not, therefore, be limited by the above description, but instead should be determined with reference to the appended claims along with their full scope of equivalents.

What is claimed is:

1. A method of coating a substrate having a solidified layer formed thereon, said method comprising:

depositing a flowable material upon said solidified layer;

forming a smooth flowable surface upon said substrate by imparting rotational movement upon said substrate followed by leveling of said flowable material in an absence of said rotational movement; and

solidifying said additional layer.

2. The method as recited in claim 1 wherein solidifying further includes exposing said flowable material to actinic energy.

3. The method as recited in claim 1 wherein forming occurs at ambient temperatures.

4. The method as recited in claim 1 wherein forming further includes terminating said rotational movement and minimizing movement of said substrate for approximately 2 to 30 minutes after termination of said rotational movement.

5. The method as recited in claim 1 wherein forming further includes rotating said substrate at approximately 4,000 revolutions per minute for less than ten seconds.

6. The method as recited in claim 1 further including forming said solidified layer by spin-coating a silicon containing flowable composition having a solvent until said solvent evaporates forming said solidified layer.

7. The method as recited in claim 1 further including forming said solidified layer by spin-coating a silicon containing flowable composition having a solvent until said solvent evaporates, forming an evaporated layer and baking said evaporated layer to form said solidified layer.

8. The method as recited in claim 1 at wherein disposing further includes providing said flowable material with solvent and forming further includes maintaining said rotational movement until said flowable material contains less that 0.1% solvent by weight.

9. A method of coating a substrate having a solidified layer formed thereon, said method comprising:

depositing a flowable material, having a solvent, upon said solidified layer;

varying a viscosity of said flowable material, at ambient temperatures, by spreading said flowable material over said solidified layer to form a flowable surface; and

solidifying said flowable material to form a second layer.

10. The method as recited in claim 9 wherein solidifying further includes exposing said flowable material to actinic energy.

11. The method as recited in claim 9 wherein varying further includes imparting rotational movement followed by terminating said rotational movement and minimizing movement of said substrate for approximately 2 to 30 minutes after termination of said rotational movement to allow leveling of said flowable surface.

12. The method as recited in claim 9 wherein varying further includes imparting rotational movement further includes rotating said substrate at approximately 4,000 revolutions per minute for less than ten seconds.

13. The method as recited in claim 9 further including forming said solidified layer by spin-coating a silicon containing flowable composition having a solvent until said solvent evaporates, forming an evaporated layer and baking said evaporated layer to form said solidified layer.

14. A method of coating a substrate having a solidified layer formed thereon, said method comprising:

depositing a flowable material including solvent upon said solidified layer;

imparting rotational movement upon said substrate to spread said flowable material over said solidified layer until said flowable material contains less that 0.1% solvent by weight to form an additional layer having a flowable surface;

leveling of said flowable surface; and

solidifying said additional layer.

15. The method as recited in claim 14 wherein solidifying further includes exposing said flowable material to actinic energy.

16. The method as recited in claim 14 wherein leveling of said flowable surface occurs at ambient temperature.

17. The method as recited in claim 14 wherein departing, leveling and solidifying occur at ambient temperatures.

18. The method as recited in claim 14 further including terminating said rotational movement and wherein leveling further includes minimizing movement of said substrate for approximately 2 to 30 minutes after termination of said rotational movement.

19. The method as recited in claim 14 wherein imparting rotational movement further includes rotating said substrate at approximately 4,000 revolutions per minute for less than ten seconds.

20. The method as recited in claim 14 further including forming said solidified layer by spin-coating a silicon containing flowable composition having a solvent until said solvent evaporates, forming an evaporated layer and baking said evaporated layer to form said solidified layer.

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