US 20130045339A1

(19) **United States**
(12) **Patent Application Publication**
Godet et al.
(10) **Pub. No.: US 2013/0045339 A1**
(43) **Pub. Date: Feb. 21, 2013**

(54) **TECHNIQUES FOR DIAMOND NUCLEATION CONTROL FOR THIN FILM PROCESSING**

(75) Inventors: **Ludovic Godet**, Boston, MA (US); **Xianfeng Lu**, Beverly, MA (US); **Anthony Renau**, West Newbury, MA (US)

(73) Assignee: **VARIAN SEMICONDUCTOR EQUIPMENT ASSOCIATES, INC.**, Gloucester, MA (US)

(21) Appl. No.: **13/210,122**

(22) Filed: **Aug. 15, 2011**

Publication Classification

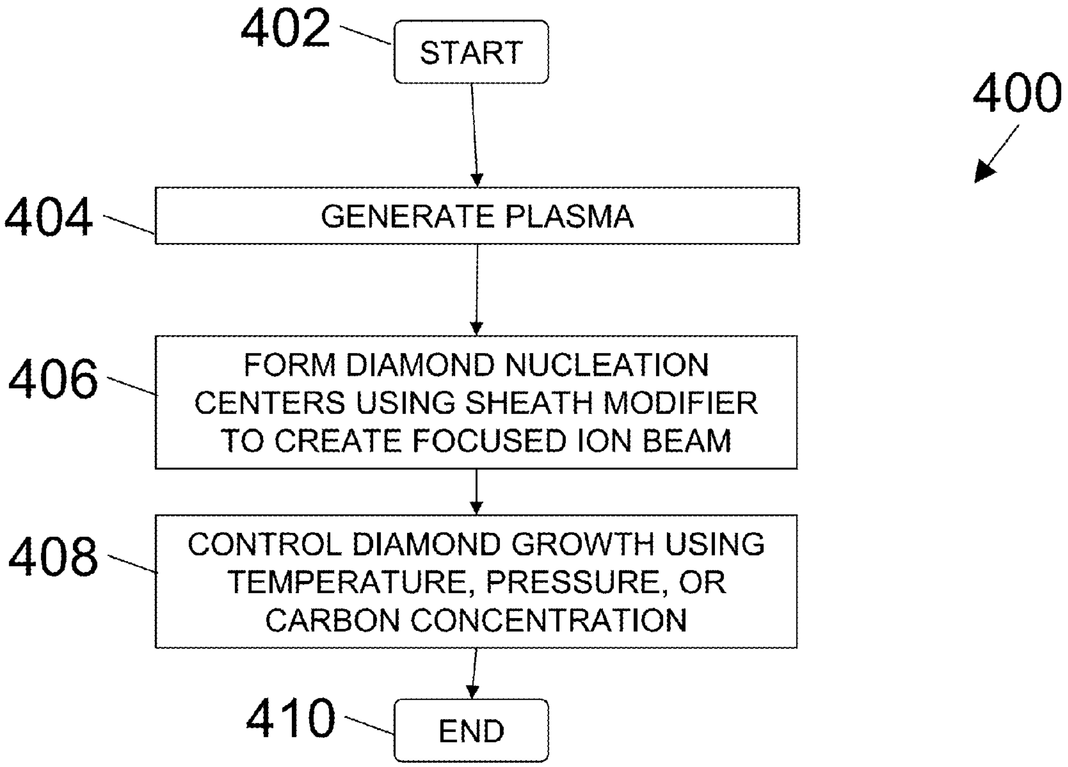
(51) **Int. Cl.**

H05H 1/24	(2006.01)
C23C 16/50	(2006.01)
B05C 11/00	(2006.01)

(52) **U.S. Cl.** **427/577**; 118/697; 118/719

(57) **ABSTRACT**

Techniques for diamond nucleation control for thin film processing are disclosed. In one particular embodiment, the techniques may be realized as a method for generating a plasma having a plurality of ions; depositing a plurality of diamond nucleation centers on a substrate with the ions in the plasma using an extraction plate having at least one gap, wherein the plasma ions pass through the at least one gap in the extraction plate to generate a focused ion beam to deposit the plurality of diamond nucleation centers; and controlling the growth of a continuous diamond film from the diamond nucleation centers on the substrate by controlling at least one of a temperature around the substrate, a temperature of the plasma, a pressure around the substrate, and a concentration of the ions in the plasma.



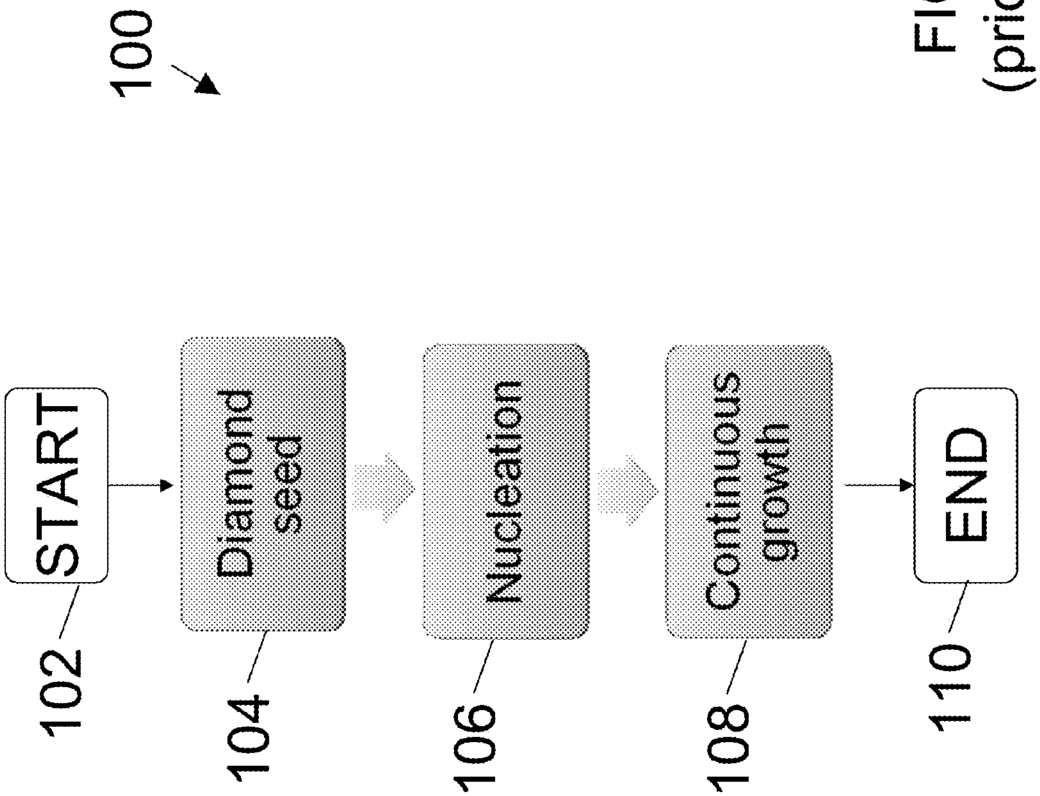


FIG. 1
(prior art)

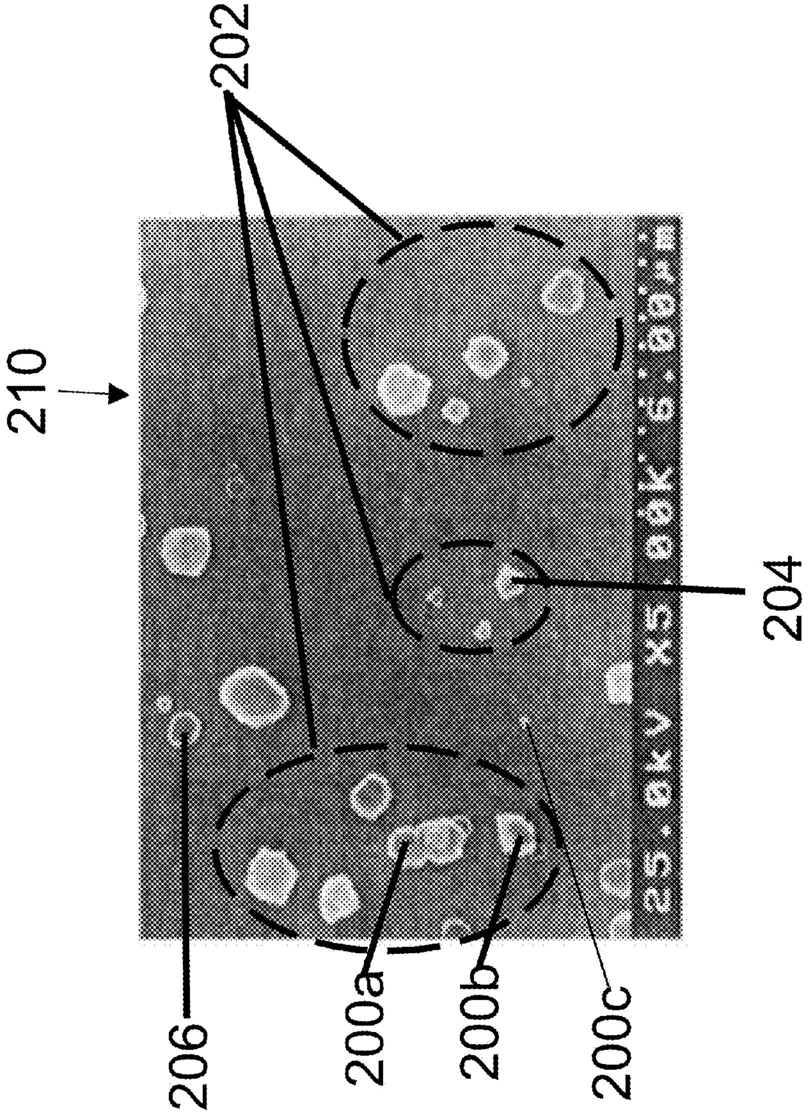


FIG. 2A
(prior art)

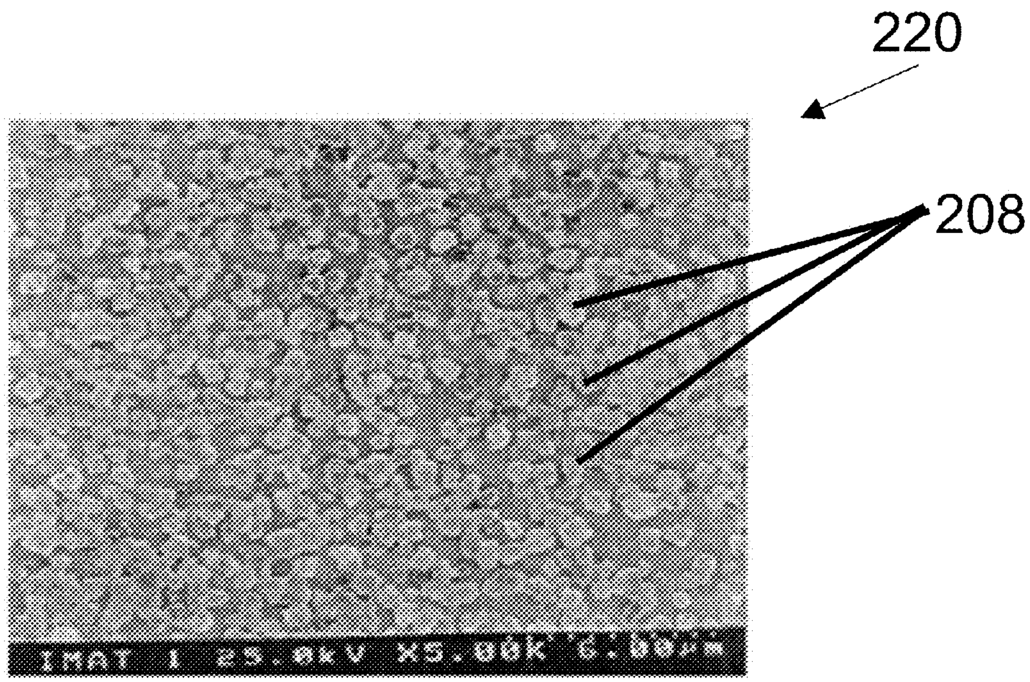


FIG. 2B
(prior art)

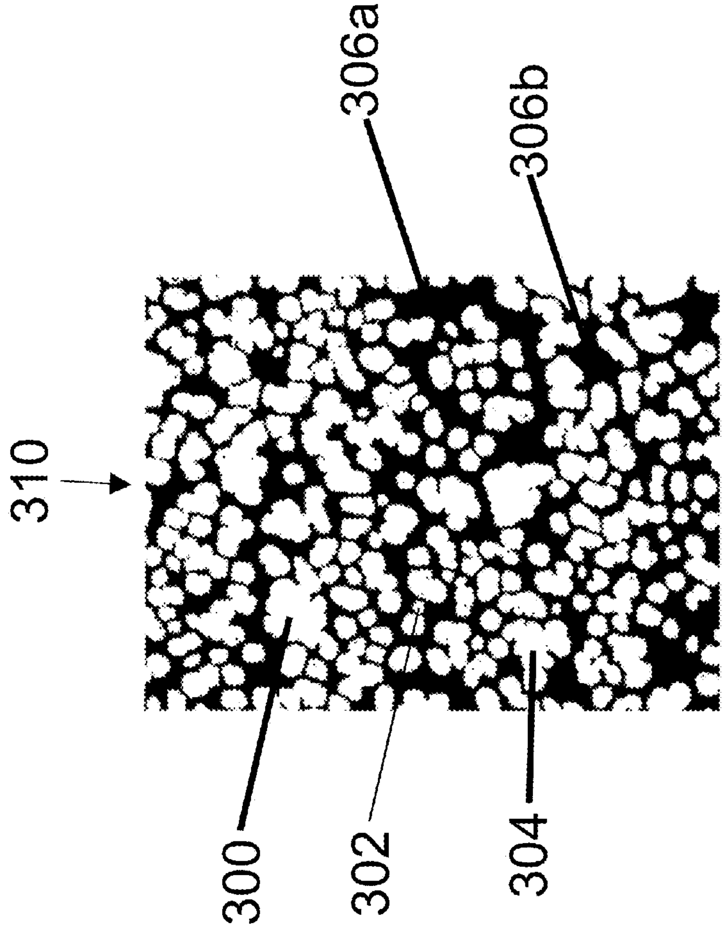


FIG. 3
(prior art)

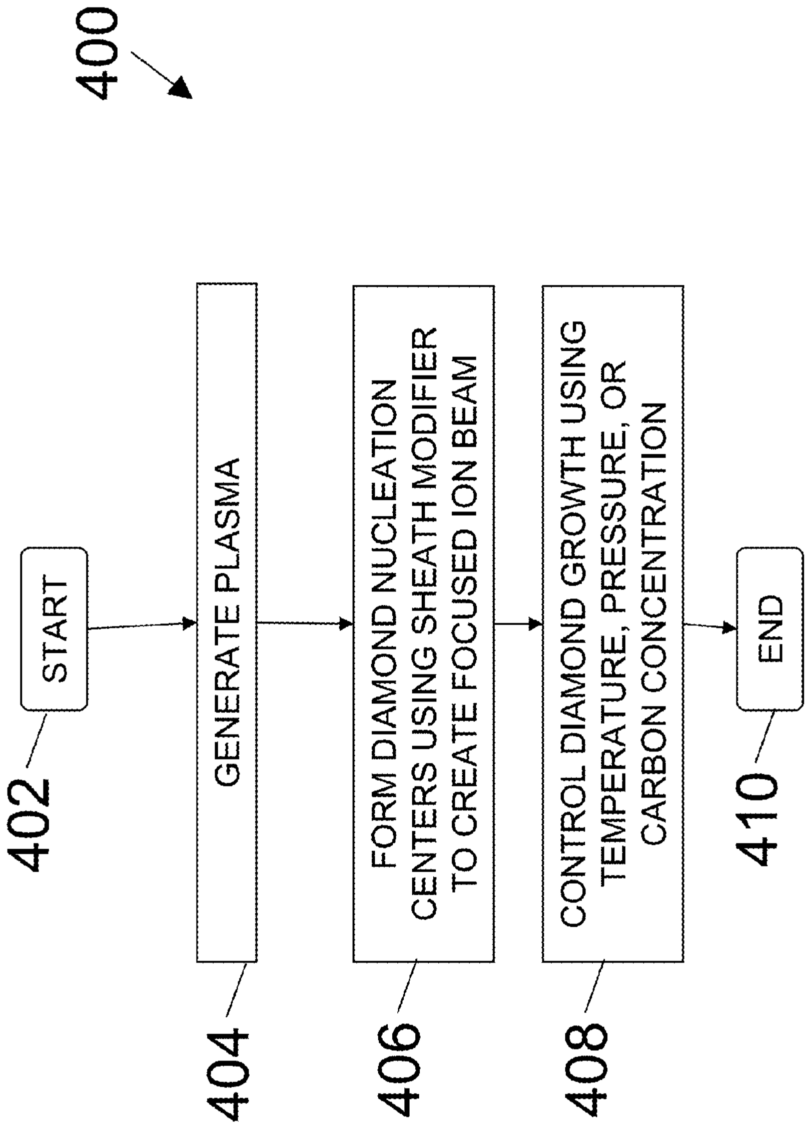

400
402
START
404
GENERATE PLASMA
406
FORM DIAMOND NUCLEATION CENTERS USING SHEATH MODIFIER TO CREATE FOCUSED ION BEAM
408
CONTROL DIAMOND GROWTH USING TEMPERATURE, PRESSURE, OR CARBON CONCENTRATION
410
END

FIG. 4

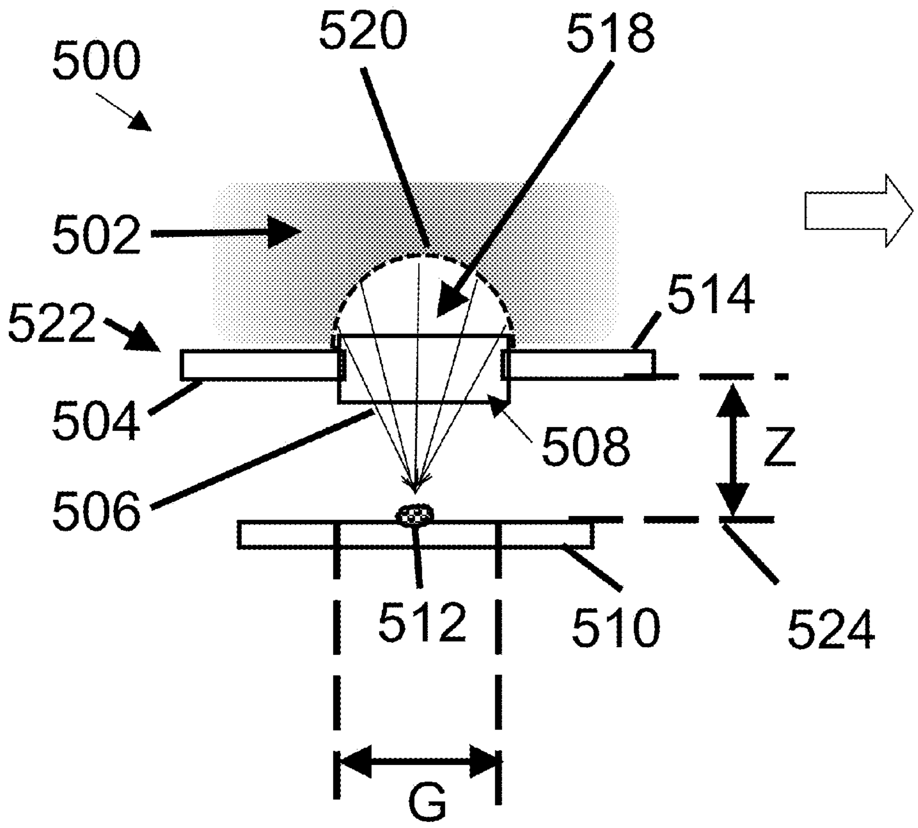

500
520
518
502
522
514
504
508
Z
506
512
510
524
G

FIG. 5A

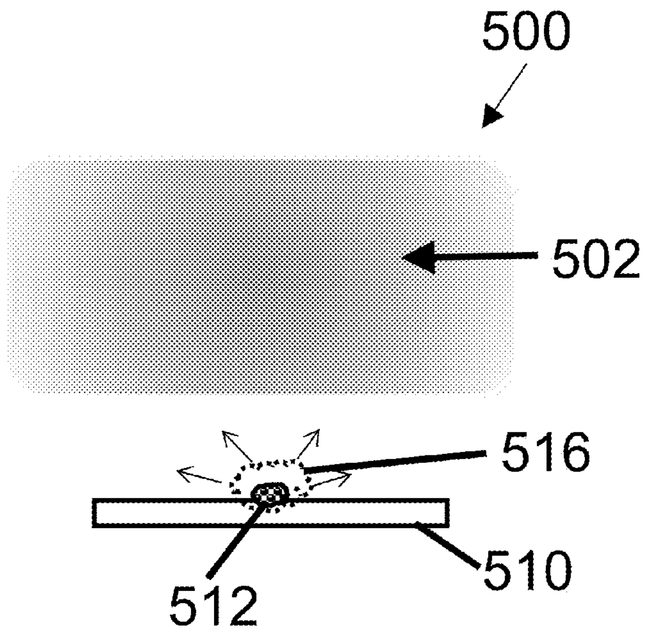

500
502
516
510
512

FIG. 5B

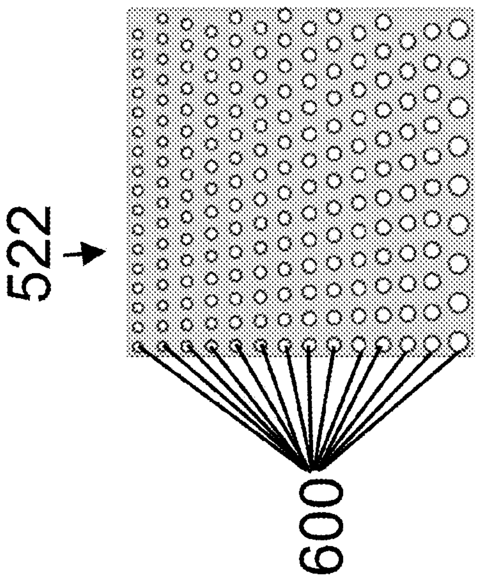


FIG. 6A

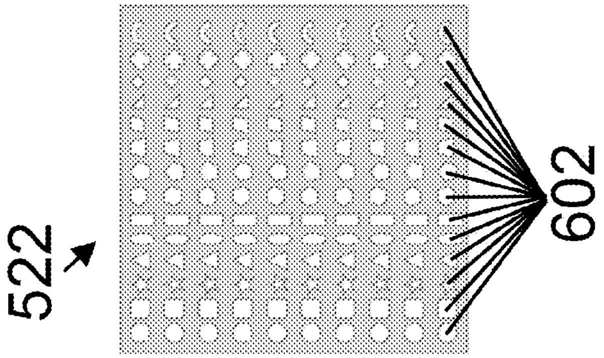


FIG. 6B

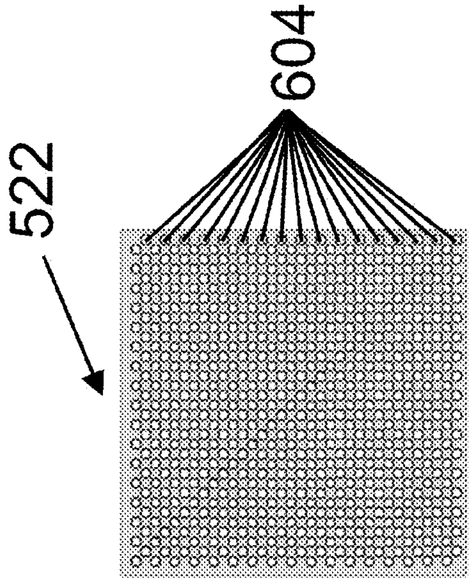


FIG. 6C

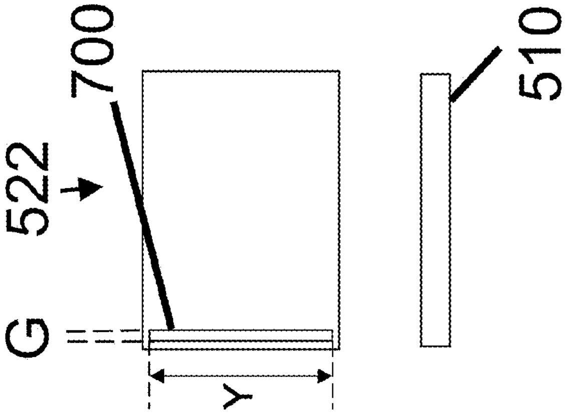


FIG. 7A

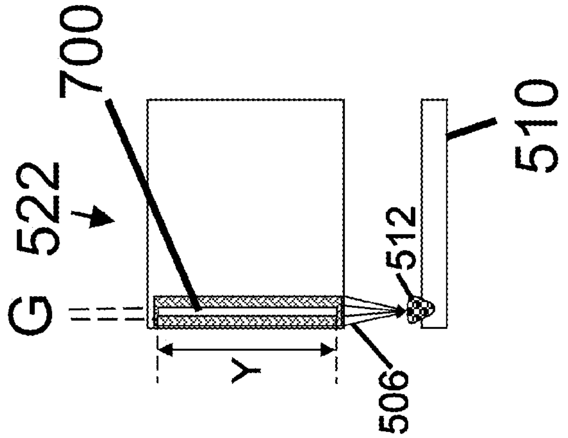


FIG. 7B

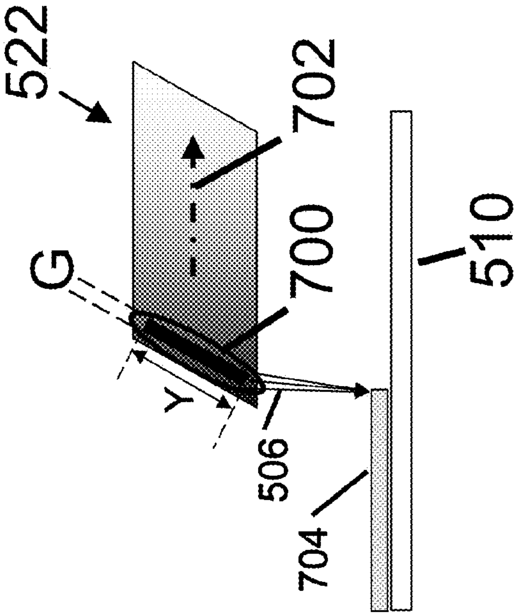


FIG. 7C

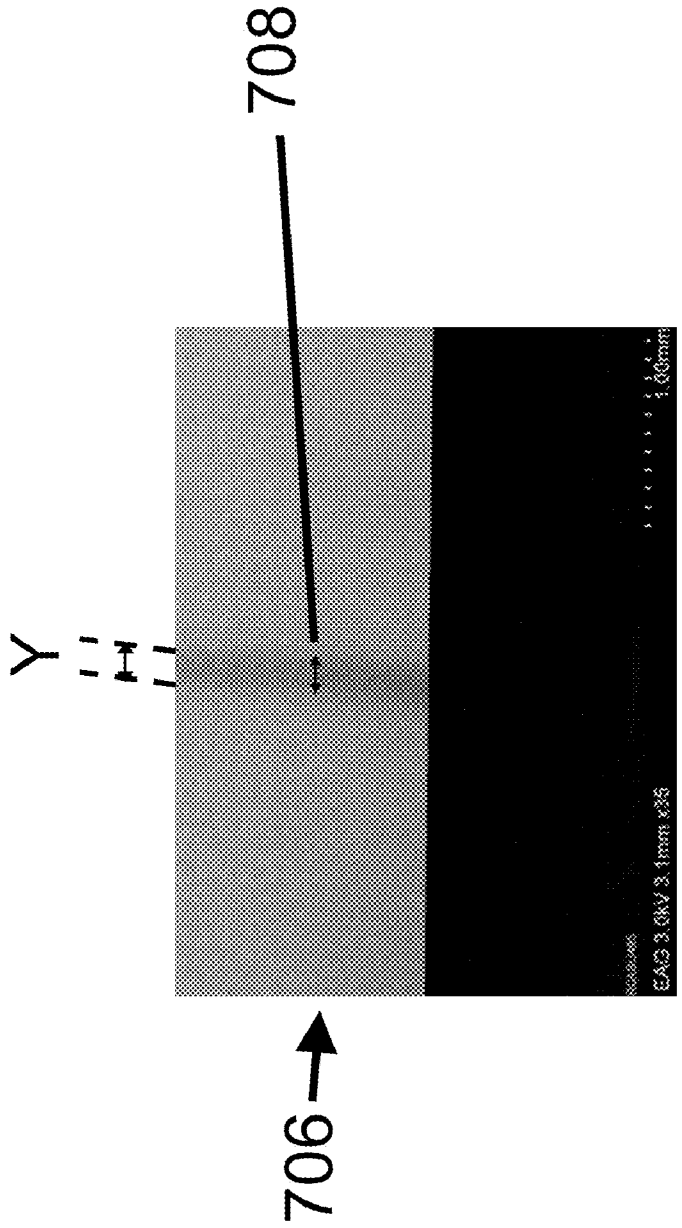


FIG. 7D

TECHNIQUES FOR DIAMOND NUCLEATION CONTROL FOR THIN FILM PROCESSING

FIELD OF THE DISCLOSURE

[0001] The present disclosure relates generally to process control and, more particularly, to techniques for diamond nucleation control for thin film processing.

BACKGROUND OF THE DISCLOSURE

[0002] The synthesis and application of diamond films has myriad applications in high technology industries. Diamond films have been deposited on various non-diamond substrates, including insulators, semiconductors and metals, ranging from single crystals to amorphous materials. The success in growing diamond thin films has stimulated interest in the unique properties of diamond for technological applications. Diamond is harder than any known solid, and exhibits the highest elastic modulus, highest atomic density, highest Debye temperature, highest acoustic velocity, and highest thermal conductivity at room temperature. In addition, diamond is chemically inert, has a very low frictional coefficient and thermal expansion coefficient, and is highly transparent from the ultraviolet to the infrared spectra. Diamond is a wide band-gap semiconductor that may be useful at high temperatures or high voltages. These properties have made the use of diamond desirable for many potential applications, such as heat spreaders, optical windows, x-ray lithography, low-friction or wear resistant surface coatings, cutting tool coatings, and active electronic device elements.

[0003] Diamond film has traditionally been grown in three steps, including diamond seed, nucleation, and formation of a continuous diamond film. Nucleation refers to the beginning process of diamond formation on a substrate. Diamond film is then grown around the diamond seeds to form a continuous thin film. Among these steps, nucleation has a significant effect on the resulting film's structure, properties and surface morphology.

[0004] Two nucleation processes have traditionally been used. One process is to pre-treat a silicon wafer in diamond powder, with the result that small diamond particles stay on the surface of the wafer and act as the nucleation centers. The other process is to use bias energy to enhance the nucleation process in the very beginning of diamond growth, but without any diamond particles on the substrate to act as diamond seeds for the nucleation process.

[0005] However, there are problems and shortcomings associated with these traditional processes. For example, it may be difficult to grow diamond films with good uniformity over a large area. These traditional processes may require high temperature and high pressure, and therefore may not be compatible with substrate materials that are susceptible to high temperature or high pressure. Also, the formed nucleation centers may not be substantially uniform in size, morphology and distribution, which may result in non-uniform diamond growth.

[0006] In view of the foregoing, it may be understood that there may be significant problems and shortcomings associated with current nucleation control technologies.

SUMMARY OF THE DISCLOSURE

[0007] Techniques for diamond nucleation control for thin film processing are disclosed. In one particular embodiment, the techniques may be realized as a method for generating a plasma having a plurality of ions; depositing a plurality of diamond nucleation centers on a substrate with the ions in the plasma using an extraction plate having at least one gap, wherein the plasma ions pass through the at least one gap in the extraction plate to generate a focused ion beam to deposit the plurality of diamond nucleation centers; and controlling the growth of a continuous diamond film from the diamond nucleation centers on the substrate by controlling at least one of a temperature around the substrate, a temperature of the plasma, a pressure around the substrate, and a concentration of the ions in the plasma.

[0008] In accordance with other aspects of this particular embodiment, the depositing a plurality of diamond nucleation centers on a substrate includes propagating the plurality of diamond nucleation centers in a direction of motion by moving the extraction plate having at least one gap and the focused ion beam in the direction of motion.

[0009] In accordance with further aspects of this particular embodiment, the at least one gap includes at least one slot having at least one of a length, a width, and a shape arranged to control at least one of a size, a distribution, and a morphology of the diamond nucleation centers on the substrate when the focused ion beam strikes the substrate to form the plurality of diamond nucleation centers.

[0010] In accordance with additional aspects of this particular embodiment, the at least one gap includes a plurality of apertures having at least one of a size, a distribution, and a shape arranged to control at least one of a size, a distribution, and a morphology of the diamond nucleation centers on the substrate when the focused ion beam strikes the substrate to form the plurality of diamond nucleation centers.

[0011] In another particular embodiment, the techniques may be realized as a system for diamond nucleation control for thin film processing, the system comprising a plasma processing module for generating a plasma having a plurality of ions; one or more extraction plates having at least one gap for forming a deposition of a plurality of diamond nucleation centers on a substrate with the plurality of ions in the plasma using an extraction plate having at least one gap, wherein the plasma ions pass through the at least one gap in the extraction plate to generate a focused ion beam to form the plurality of diamond nucleation centers; and a temperature controller for controlling the growth of a continuous diamond film on the substrate by controlling at least one of a temperature around the substrate, a temperature of the plasma, a pressure around the substrate, and a concentration of ions in the plasma.

[0012] The present disclosure will now be described in more detail with reference to particular embodiments thereof as shown in the accompanying drawings. While the present disclosure is described below with reference to particular embodiments, it should be understood that the present disclosure is not limited thereto. Those of ordinary skill in the art having access to the teachings herein will recognize additional implementations, modifications, and embodiments, as well as other fields of use, which are within the scope of the present disclosure as described herein, and with respect to which the present disclosure may be of significant utility.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] In order to facilitate a fuller understanding of the present disclosure, reference is now made to the accompanying drawings, in which like elements are referenced with like numerals. These drawings should not be construed as limiting the present disclosure, but are intended to be illustrative only.

[0014] FIG. **1** shows a flow diagram for a method of growing a diamond thin film in accordance with an embodiment of the present disclosure.

[0015] FIGS. **2**A-**2**B show photographs from a scanning electron microscope of diamond nucleation on a substrate in accordance with an embodiment of the present disclosure.

[0016] FIG. **3** shows a photograph of nucleation centers formed in accordance with an embodiment of the present disclosure.

[0017] FIG. **4** shows a flow diagram of a method for focused-ion-beam-assisted diamond nucleation in accordance with an embodiment of the present disclosure.

[0018] FIG. **5**A-**5**B show block diagrams for a system for focused-ion-beam-assisted diamond nucleation in accordance with an embodiment of the present disclosure.

[0019] FIGS. **6**A-**6**C show top views of extraction plates used in focused-ion-beam-assisted diamond nucleation in accordance with an embodiment of the present disclosure.

[0020] FIGS. **7**A-**7**D show top views and a perspective view of extraction plates used in focused deposition by sheath engineering, and a photograph from a scanning electron microscope of focused deposition by sheath engineering in accordance with an embodiment of the present disclosure.

DETAILED DESCRIPTION OF EMBODIMENTS

[0021] The present disclosure relates to techniques for using focused ion beam deposition for diamond nucleation control in thin film processing. The diamond film grown according to the present techniques shows improved surface morphology. The improved surface morphology is seen in the diamond film exhibiting improved uniformity in size, morphology, and distribution. The present techniques include a method for plasma processing a large area diamond thin film using a focused ion beam through plasma sheath engineering. Advantageously, the present techniques result in well-controlled growth of diamond nucleation centers having improved uniformity in size, morphology and distribution.

[0022] Referring now to FIG. **1**, there is shown a flow diagram for a method **100** of growing diamond thin film in accordance with an embodiment of the present disclosure. FIG. **1** includes a step **104** of depositing diamond seed on a substrate, a step **106** of nucleation, and a step **108** of continuous growth of thin film. The method **100** starts at step **102** and proceeds to step **104**, in which diamond seed is deposited on a substrate. The diamond seed determines the quality of the nucleation center, the growth mode, the surface morphology, the grain size, and the grain morphology. At step **106**, nucleation refers to the process of forming nucleation centers from the diamond seeds. Step **106** of nucleation has a significant effect on the structure, properties, and surface morphology of the resulting continuous diamond thin film. At step **108**, formation of a continuous thin film results from growth starting from the diamond seeds. The method **100** ends at step **110**.

[0023] Referring to FIGS. **2**A-**2**B, there are shown scanning electron microscope (SEM) photographs of diamond nucleation on a substrate in accordance with an embodiment of the present disclosure. FIG. **2**A illustrates a SEM photograph of diamond nucleation on a small copper substrate **210** without pre-treatment. FIG. **2**A includes nucleation centers **200***a-c*, **204**, and **206**, areas **202** of non-uniform nucleation centers, and a substrate **210**. Nucleation centers **200***a-c* vary in size. Similarly, areas **202** show that distribution can vary among the nucleation centers **200***a-c* within each area **202**, as there are large areas of substrate **210** showing through where the nucleation centers **200***a-c* are not uniformly distributed. Lastly, the nucleation centers **200***a-c* exhibit varying morphology. Morphology refers to the roughness or smoothness of the nucleation centers **200***a-c*. For example, nucleation center **204** exhibits a relatively rougher morphology, being shaped similar to a pentagon when viewed at high magnification. On the other hand, nucleation center **206** exhibits a relatively smoother morphology, appearing round when viewed at high magnification.

[0024] FIG. **2**B illustrates a SEM photograph of diamond nucleation on a small copper substrate **220** that has been pre-treated by polishing with diamond powder. FIG. **2**B includes nucleation centers **208** and a substrate **220**. If the substrate **220** is of small area and is polished with diamond powder, it may be possible to grow a continuous diamond film. Nucleation centers **208** may exhibit uniform size, morphology, and distribution throughout the substrate **220**. However, one shortcoming associated with nucleation control technologies has been difficulty achieving similar results in large areas. The main reason for this shortcoming is the difficulty of achieving substantially uniform diamond seed size, morphology and distribution.

[0025] Referring to FIG. **3**, there is shown a photograph of nucleation centers **300**, **302**, and **304** formed in accordance with an embodiment of the present disclosure. FIG. **3** includes nucleation centers **300**, **302**, and **304**, gaps **306***a*, **306***b* in uniformity of the nucleation centers, and a substrate **310**. Two diamond nucleation processes have traditionally been used to generate such nucleation centers **300**, **302**, and **304**. One such process is to pre-treat a silicon wafer in diamond powder. The silicon wafer acts as a substrate. Small diamond particles may stay on the surface of the silicon wafer and act as the nucleation centers **300**, **302**, and **304**. As shown in FIG. **3**, the nucleation centers **300**, **302**, and **304** grown according to traditional methods are all of differing sizes. As described above, these traditional methods require high temperature and high pressure, and may not be compatible with substrate materials that are susceptible to high temperature or high pressure. Furthermore, the distribution of the nucleation centers may not be uniform, which may result in gaps **306***a*, **306***b* through which the substrate **310** can be seen. Referring to FIG. **1**, in step **108** of the diamond growth process **100**, non-uniform nucleation centers may result in non-uniform diamond growth.

[0026] Referring to FIG. **4**, there is shown a flow diagram of a method **400** for focused-ion-beam-assisted diamond nucleation in accordance with an embodiment of the present disclosure. FIG. **4** includes a step **404** of generating plasma, a step **406** of forming diamond nucleation centers using a sheath modifier, and a step **408** of controlling diamond growth using temperature or carbon concentration. The method **400** starts at step **402** and proceeds to step **404**, at which plasma may be generated. At step **406**, a sheath modifier may be used to focus the plasma into a focused ion beam for deposition of nucleation centers. In one embodiment, the extraction plates may be made substantially of quartz. Extraction plates may be used having apertures or slots as masks to control the size, morphology, and distribution of nucleation centers In various embodiments, sheath hardware is used having apertures of small size. At step **408**, temperature control may be used to control diamond growth. In some embodiments, the presence or absence of localized heat may be used to control diamond growth. The method **400** ends at step **410**. The steps **404**, **406**, and **408** will be described in further detail below.

[0027] Referring to FIGS. **5**A-**5**B, there are shown block diagrams for focused-ion-beam-assisted diamond nucleation in accordance with an embodiment of the present disclosure. FIG. **5**A illustrates the nucleation phase, and FIG. **5**B illustrates growing continuous thin film. As illustrated in FIG. **4**, at step **406**, diamond nucleation centers may be formed using a sheath modifier to modify plasma sheaths using extraction plates and strong bias energy to generate a focused ion beam. In some embodiments, the strong bias energy may be less than three kiloelectronvolts (keV). FIG. **5**A illustrates step **404** showing a system **500** having a plasma sheath modifier. The system **500** employs in-situ focused surface bombardment **506** under an applied negative bias on a conductive substrate **510**. FIG. **5**A includes a system **500**, plasma **502**, an extraction plate **522** having panels **514** and **522**, a plasma sheath **518** having a boundary **520**, a focused ion beam **506**, an aperture **508**, a substrate **510** having a horizontal plane **524**, and a diamond nucleation center **512**. As illustrated in FIG. **4**, at step **404**, plasma may be generated for use in focusing an ion beam on a substrate. As illustrated in FIG. **5**, plasma **502** may be generated via a plasma processing module or a number of known processes. The plasma **502** is generally a quasi-neutral collection of ions and electrons.

[0028] The ions typically have a positive charge while the electrons have a negative charge. The plasma **502** may have an electric field of, for example, approximately 0-15 V/cm in the bulk of the plasma **502**. In the system **500** containing the plasma **502**, ions from the plasma **502** are attracted toward a substrate **510**. These ions may be attracted with sufficient energy to be implanted into the substrate **510**. The plasma **502** is bounded by a region proximate the substrate **510** referred to as a plasma sheath **518**. The plasma sheath **518** is a region that has fewer electrons than does the plasma **502**. Hence, the differences between the negative and positive charges cause a sheath potential in the plasma sheath **502**. The light emission from this plasma sheath **518** is less intense than the plasma **140** because fewer electrons are present and, hence, few excitation-relaxation collisions occur. Thus, the plasma sheath **242** is sometimes referred to as “dark space.”

[0029] The plasma sheath modifier **522** is configured to modify an electric field within the plasma sheath **518** to control a shape of a boundary **520** between the plasma **502** and the plasma sheath **518**. Accordingly, ions that are attracted from the plasma **502** across the plasma sheath **518** may strike the substrate **510** at a large range of incident angles. This plasma sheath modifier **522** may be referred to as, for example, an extraction plate, focusing plate or sheath engineering plate.

[0030] As shown in FIG. **5**A, the extraction plate **522** includes a pair of panels **504** and **514** defining an aperture **508** therebetween having a horizontal spacing (G). The panels **504** and **514** may be an insulator, semiconductor, or conductor. In other embodiments, the extraction plate **522** may include only one panel or more than two panels. The panels **504** and **514** may be a pair of sheets having a thin, flat shape. In other embodiments, the panels **504** and **514** may be other shapes such as tube-shaped, wedge-shaped, and/or have a beveled edge proximate the aperture. The panels **504** and **514** also may be positioned a vertical spacing (Z) above the plane **524** defined by the front surface of the substrate **510**. In one embodiment, the vertical spacing (Z) may be about 1.0 to 10.0 mm.

[0031] Ions may be attracted from the plasma **502** across the plasma sheath **518** by different mechanisms. In one instance, the substrate **510** is biased using an energy differential to attract ions from the plasma **502** across the plasma sheath **518**. In another instance, a plasma source that generates the plasma **502** and walls surrounding the plasma **502** are biased positively and the substrate **510** may be grounded. In one particular embodiment, the biasing may be pulsed. In yet another instance, electric or magnetic fields are used to attract ions from the plasma **502** toward the substrate **510**.

[0032] Advantageously, the extraction plate **522** modifies the electric field within the plasma sheath **518** to control a shape of the boundary **520** between the plasma **502** and the plasma sheath **518**. The boundary **520** between the plasma **502** and the plasma sheath **518** may have a convex shape relative to the plane **524** in one instance. When the substrate **510** is biased, for example, the ions are attracted across the plasma sheath **518** through the aperture **508** between the panels **504** and **514** at a large range of incident angles. Depending on a number of factors including, but not limited to, the horizontal spacing (G) between the panels **504** and **514**, the vertical spacing (Z) of the panels **504** and **514** above the plane **524**, the dielectric constant of the panels **504** and **514**, or other process parameters of the plasma **502**, the range of incident angles may be between +60° and −60° centered about 0°. FIG. **5**A illustrates the substrate **510** at a vertical spacing (Z) such that the ions are focused on the diamond nucleation center **512**.

[0033] Further, the plasma preferably has a relatively higher concentration of molecules capable of forming carbon ions, compared to the concentration used in the growth step shown in FIG. **5**B. In example embodiments, the plasma **502** preferably has a high methane concentration, comprising about 10% methane (CH_4) and about 90% hydrogen (H_2). Other percentages of molecules capable of forming carbon ions may be used. Other species of molecules beyond methane may be used, such as a fluorocarbon CF_4, a hydrocarbon C_xH_y, or a hydrofluorocarbon CHF_3. Other gases instead of, or in addition to, hydrogen may also be used, including inert gases such as He, Ne, Ar, Kr or Xe, or combinations thereof such as H_2, He, and Ar. An applied electric field may increase an ionization degree of the neutral gas molecules, energy of the ions, and a surface ion bombardment rate.

[0034] The plasma **502** is focused into a focused ion beam **506** using an extraction plate **522**. In some embodiments, the extraction plate **522** is made of quartz, a semiconductor material, or a conductor material. The extraction plate **522** has an aperture **508** through which the focused beam **506** exits, and bombards or strikes the substrate **510**. During the bombardment, the ionic species alter the surface of the substrate **510** and create surface structures that act as seeds **512** for diamond growth. As illustrated in FIG. **4**, at step **406**, the extraction plate **522** is used to focus the deposition of the diamond growth seeds **512**.

[0035] In alternative embodiments, the system **500** may use an insulating substrate **510** with pulsed bias energy and charge neutralization knobs between pulses. With an insulating substrate **510**, if the bias energy is active at all times, a charge from the ions may accumulate because the substrate **510** is insulated and the charge cannot dissipate. Therefore, future ions may not be able to focus on the insulating substrate

510 to deposit the diamond nucleation centers **512**. With pulsed bias energy, in some embodiments the energy may have a pulse of 200 μs whereby during 100 μs, the energy is on, or pulsed, and during 100 μs, the energy is off, or a "knob." On an insulating substrate **510**, when the pulsed bias energy is on, a charge may build up on the substrate **510**. When the pulsed bias energy is off, the charge may dissipate, which may allow additional ions to focus on the substrate during the next pulse. Accordingly, diamond nucleation centers **512** may still be formed on an insulating substrate **510**.

[0036] In further embodiments, the system **500** may use an insulating substrate **510** with pulsed bias energy in a multi-set-point radio frequency (MSPRF) mode. In MSPRF mode, a single pulse of the energy may be divided into four phases. The phases may include pre, on, post, and final. The length and power for each phase may be controlled separately, providing more flexibility to tune the plasma **502**.

[0037] FIG. **5**B illustrates a block diagram of ion-assisted diamond growth in accordance with an embodiment of the present disclosure. FIG. **5**B includes the system **500** having the plasma processing module and a temperature controller, the plasma **502**, the substrate **510**, the diamond nucleation center **512**, and ion-assisted diamond growth **516**. As illustrated in FIG. **4**, at step **408**, temperature control may be applied to the substrate **510** to achieve continuous diamond thin film growth. This growth step is shown in further detail in FIG. **5**B. After formation of the diamond seeds **512**, the extraction plate **522** is removed. The methane concentration of the plasma **502** may then be reduced. The plasma **502** is preferably reduced to a low methane concentration, comprising about 1%-2% methane (CH_4) and about 98%-99% hydrogen (H_2). Ion-assisted diamond growth **516** may occur starting from the diamond seed **512** deposited in FIG. **5**A. Because of the presence of methane, the plasma **502** may still have a concentration of molecules capable of forming carbon ions. Accordingly, carbon ions may be able to collect around the diamond nucleation center **512** and form the thin film. The diamond growth **516** may occur along the full substrate **510**, or if a ribbon-shaped or slot aperture is used, the diamond may be grown in a ribbon, or focused line **704** (shown in FIGS. **7**A-**7**D). As described in further detail below, the plasma processing module may control the temperature of the plasma. Because the extraction plate **522** is removed, the substrate **510** is in more direct contact with the plasma **502**. Controlling the temperature of the plasma **502** controls the temperature around the substrate **510** for the diamond growth **516**. In some embodiments, an angle controller may control the angle of the substrate **510** for the diamond growth **516** in a chosen direction, to control the shape of the resulting diamond thin film. The angle controller controls the angle of the substrate which changes the angle of the ions bombarding the surface from the plasma **502**. The changed angle allows the system **500** to control the focal point of the focused ion beam which may alter the growth of the diamond film or the crystal orientation of the resulting diamond film.

[0038] Referring to FIGS. **6**A-**6**C, there are shown top views of extraction plates **522** having a plurality of apertures used in focused-ion-beam-assisted diamond nucleation in accordance with an embodiment of the present disclosure. FIG. **6**A illustrates a top view of an extraction plate **522** to control seed size in accordance with an embodiment of the present disclosure. FIG. **6**A illustrates that the size of the nucleation centers **512** (shown in FIGS. **5**A-**5**B) can be controlled and adjusted by varying aperture size **600**. FIG. **6**A includes the extraction plate **522** and apertures of varying size **600**. For illustrative purposes, each row of apertures shows a varying aperture size **600** increasing from top to bottom down the extraction plate **522**. In other embodiments, parameters of the plasma **502** (shown in FIGS. **5**A, **5**B) may be controlled and adjusted to achieve the same result of controlling seed size. Example plasma parameters include power, bias energy, and pressure.

[0039] Similar to FIG. **6**A, FIG. **6**B illustrates a top view of an extraction plate **522** to control seed morphology in accordance with an embodiment of the present disclosure. FIG. **6**B includes the extraction plate **522** and apertures of varying shape **602**. The morphology of the nucleation centers **512** can be controlled and adjusted by varying the aperture shape **602**. For illustrative purposes, each column of apertures shows a varying aperture shape **602**. After a desired aperture size and shape are chosen, an extraction plate **522** having apertures of substantially uniform size and shape may be used to achieve improved uniformity in seed size and seed morphology.

[0040] FIG. **6**C illustrates a top view of an extraction plate **522** to control the distribution of the diamond seeds **512** in accordance with an embodiment of the present disclosure. FIG. **6**C includes the extraction plate **522** and apertures of substantially uniform size, shape, and distribution **604**. As illustrated in FIG. **4**, at step **406**, the extraction plates **522** are used to control distribution of the diamond nucleation centers **512** (shown in FIGS. **5**A-**5**B). In some embodiments, to control the distribution of diamond nucleation centers **512**, the extraction plate **522** having an array of small apertures **508** (shown in FIG. **5**A) may be used as a mask to define the distribution **604** of grown diamond particles. That is, the distribution of nucleation centers **512** may be easily controlled by varying aperture distribution **604** in the extraction plate **522**. Through use of the extraction plate **522**, the nucleation centers **512** may be formed in the regions of the substrate **510** exposed by small apertures **508** in the extraction plate **522**. The focused ion beam **506** (shown in FIG. **5**A) is then used to deposit diamond seeds **512** onto the substrate **510** (shown in FIGS. **5**A-**5**B). Advantageously, the result of adjusting the aperture size, shape, and distribution in the extraction plate **522**, or of controlling the plasma parameters, is that the diamond seed size, morphology, and distribution may be controlled when deposited onto the substrate **510**. As described in FIG. **5**A, the system **500** may also adjust the vertical distance (Z) between the extraction plate **522** and the substrate **510** to control the diamond seed size, morphology, and distribution.

[0041] Referring to FIGS. **7**A-**7**C, there are shown top and perspective views of an extraction plate **522** having at least one rectangular slot used in focused-ion-beam-assisted diamond nucleation in accordance with an embodiment of the present disclosure. FIG. **7**A includes a substrate **510** and an extraction plate **522** with a rectangular slot **700**. The extraction plate **522** having a rectangular slot **700** may be used with a substrate **510**. The extraction plate **522** has a vertical length (Y) and a horizontal gap (G). As illustrated in FIG. **4** in step **406**, a sheath modifier may be used to grow crystal seeds using a focused ion beam. FIG. **7**B includes a focused ion beam **506** created by the sheath modifier, the substrate **510**, a diamond seed **512**, and the extraction plate **522** with rectangular slot **700**. FIG. **7**B illustrates that diamond seed **512** may be created using an extraction plate **522** with rectangular slot **700**. The vertical length (Y) and the horizontal gap (G) (shown in FIG. **7**A) control the size, morphology, and distribution of the resulting ribbon of diamond seed **512** formed by the focused ion beam **506**. FIG. **7**C includes a focused ion beam **506** created by the sheath modifier, the substrate **510**, a diamond seed **512**, the extraction plate **522** with rectangular slot **700**, a direction **702** of motion, and a diamond layer **704**. FIG. **7**C illustrates crystal propagation by moving the extraction plate **522** in a direction **702** of motion. This scanning of the extraction plate **522** across the substrate **510** in a direction **702** of motion may result in a diamond layer **704** being created in a focused deposition on the substrate **510**. The vertical length (Y) of the extraction plate **522** controls the width of the resulting focused deposition.

[0042] FIG. **7**D illustrates an image **706** from a scanning electron microscope of focused deposition by sheath engineering in accordance with an embodiment of the present disclosure. FIG. **7**D includes a line structure **708** of focused width. FIG. **7**D shows a line **708** having a width of about 133 micrometers (μm). The line **708** results from the scanning process illustrated in FIGS. **7**A-**7**C across the substrate **510**. To deposit the line structure **704**, an extraction plate **522** with at least one rectangular slot **700** may be used (illustrated in FIGS. **7**A-**7**C). During the deposition, the extraction plate **522** may be moved to the top of a silicon wafer. The silicon wafer may be used as the substrate **510**. Only ions crossing the rectangular slot **700** of the extraction plate **522** may be deposited on the surface of the silicon wafer substrate **510**. The shape, gap size (G), and vertical length (Y) of the rectangular slot **700** may determine the morphology and size of the deposition line **708**. The ratio of line width to vertical length (Y) may be over 10:1, illustrating that the deposition is focused.

[0043] As illustrated in FIG. **4** at step **408**, temperature control may be employed to selectively grow diamond. The diamond growth may result from the use of localized heat delivered by a focused ion beam **506** (shown in FIG. **5**A). The temperature around the substrate **510** may have a significant effect on diamond growth. Using traditional methods, below a critical temperature and a critical pressure, no diamond may be grown, even with traditional methods applying bias energy. Traditional methods require critical temperatures of about 800° C.-900° C. or higher and/or critical pressures of about 30 Torr. Advantageously, the present disclosure allows diamond growth at significantly lower temperatures and significantly lower pressures. In some embodiments, the critical temperature may be about 250° C. or even lower. The critical pressure may be about 30 mTorr or even lower. To realize selective diamond growth, in the present disclosure, the plasma processing module or a temperature controller may control the temperature of the plasma **502**, or around the substrate **510** (shown in FIGS. **5**A-**5**B). Advantageously, as described above, the critical temperature for a substrate and the critical pressure around a substrate according to the present disclosure may be well below the traditional critical temperature and traditional critical pressure required for traditional diamond growth.

[0044] At this point it should be noted that diamond nucleation control in accordance with the present disclosure as described above may involve the processing of input data and the generation of output data to some extent. This input data processing and output data generation may be implemented in hardware or software. For example, specific electronic components may be employed in a focused ion beam generator or similar or related circuitry for implementing the functions associated with diamond nucleation control in accordance with the present disclosure as described above. Alternatively, one or more processors operating in accordance with instructions may implement the functions associated with diamond nucleation control in accordance with the present disclosure as described above. If such is the case, it is within the scope of the present disclosure that such instructions may be stored on one or more non-transitory processor readable storage media (e.g., a magnetic disk or other storage medium), or transmitted to one or more processors via one or more signals embodied in one or more carrier waves.

[0045] The present disclosure is not to be limited in scope by the specific embodiments described herein. Indeed, other various embodiments of and modifications to the present disclosure, in addition to those described herein, will be apparent to those of ordinary skill in the art from the foregoing description and accompanying drawings. Thus, such other embodiments and modifications are intended to fall within the scope of the present disclosure. Further, although the present disclosure has been described herein in the context of at least one particular implementation in at least one particular environment for at least one particular purpose, those of ordinary skill in the art will recognize that its usefulness is not limited thereto and that the present disclosure may be beneficially implemented in any number of environments for any number of purposes. Accordingly, the claims set forth below should be construed in view of the full breadth and spirit of the present disclosure as described herein.

1. A method for diamond nucleation control for thin film processing, the method comprising:

generating a plasma having a plurality of ions;

depositing a plurality of diamond nucleation centers on a substrate with the ions in the plasma using an extraction plate having at least one gap, wherein the plasma ions pass through the at least one gap in the extraction plate to generate a focused ion beam to deposit the plurality of diamond nucleation centers; and

controlling the growth of a continuous diamond film from the diamond nucleation centers on the substrate by controlling at least one of a temperature around the substrate, a temperature of the plasma, a pressure around the substrate, and a concentration of the ions in the plasma.

2. The method of claim **1**, wherein the depositing a plurality of diamond nucleation centers on a substrate includes propagating the plurality of diamond nucleation centers in a direction of motion by moving the extraction plate having at least one gap and the focused ion beam in the direction of motion.

3. The method of claim **1**, wherein the at least one gap includes at least one slot having at least one of a length, a width, and a shape arranged to control at least one of a size, a distribution, and a morphology of the diamond nucleation centers on the substrate when the focused ion beam strikes the substrate to form the plurality of diamond nucleation centers.

4. The method of claim **1**, wherein the at least one gap includes a plurality of apertures having at least one of a size, a distribution, and a shape arranged to control at least one of a size, a distribution, and a morphology of the diamond nucleation centers on the substrate when the focused ion beam strikes the substrate to form the plurality of diamond nucleation centers.

5. The method of claim **4**, wherein the plurality of apertures is configured according to at least one of size, shape, and distribution to result in at least one of a substantially uniform size, a substantially uniform morphology, and a substantially uniform distribution of the diamond nucleation centers.

6. The method of claim **1**, wherein the controlling the growth of the continuous diamond film on the substrate includes controlling at least one of a localized temperature and a localized pressure around regions of the substrate to stay around at least one of a critical temperature and a critical pressure for diamond growth when masked by the extraction plate.

7. The method of claim **6**, wherein the critical temperature is below about 250° C.

8. The method of claim **6**, wherein the critical pressure is below about 30 mTorr.

9. The method of claim **1**, wherein the depositing the plurality of diamond nucleation centers includes the plasma having a higher methane concentration; and wherein the controlling the growth of the continuous diamond film includes the plasma having a lower methane concentration to control the concentration of the ions in the plasma.

10. The method of claim **9**, wherein the higher methane concentration is about 10%.

11. The method of claim **9**, wherein the lower methane concentration is about 1%-2%.

12. At least one processor readable storage medium storing a computer program of instructions configured to be readable by at least one processor for instructing the at least one processor to execute a computer process for performing the method as recited in claim **1**.

13. A system for diamond nucleation control for thin film processing, the system comprising:

a plasma processing module for generating a plasma having a plurality of ions;

one or more extraction plates having at least one gap for depositing of a plurality of diamond nucleation centers on a substrate with the plurality of ions in the plasma using an extraction plate having at least one gap, wherein the plasma ions pass through the at least one gap in the extraction plate to generate a focused ion beam to form the plurality of diamond nucleation centers; and

a temperature controller for controlling the growth of a continuous diamond film on the substrate by controlling at least one of a temperature around the substrate, a temperature of the plasma, a pressure around the substrate, and a concentration of ions in the plasma.

14. The system of claim **13**, wherein the depositing a plurality of diamond nucleation centers on a substrate includes propagating the plurality of diamond nucleation centers in a direction of motion by moving the extraction plate having at least one gap and the focused ion beam in the direction of motion.

15. The system of claim **13**, wherein the at least one gap includes at least one slot having at least one of a length, a width, and a shape arranged to control at least one of a size, a distribution, and a morphology of the diamond nucleation centers on the substrate when the focused ion beam strikes the substrate to form the plurality of diamond nucleation centers.

16. The system of claim **13**, wherein the at least one gap includes a plurality of apertures having at least one of a size, a distribution, and a shape arranged to control at least one of a size, a distribution, and a morphology of the diamond nucleation centers on the substrate when the focused ion beam strikes the substrate to form the plurality of diamond nucleation centers.

17. The system of claim **13**, wherein the controlling the growth of the continuous diamond film on the substrate includes controlling at least one of a localized temperature and a localized pressure around regions of the substrate to stay around at least one of a critical temperature and a critical pressure for diamond growth when masked by the extraction plate.

18. The system of claim **13**, wherein the depositing the plurality of diamond nucleation centers includes the plasma having a higher methane concentration; and wherein the controlling the growth of the continuous diamond film includes the plasma having a lower methane concentration to control the concentration of the ions in the plasma.

19. The system of claim **18**, wherein the higher methane concentration is about 10%; and wherein the lower methane concentration is about 1%-2%.

20. An article of manufacture for diamond nucleation control for thin film processing, the article of manufacture comprising:

at least one processor readable storage medium; and

instructions stored on the at least one medium;

wherein the instructions are configured to be readable from the at least one medium by at least one processor and thereby cause the at least one processor to operate so as to:

generate a plasma having a plurality of ions;

deposit a plurality of diamond nucleation centers on a substrate with the ions in the plasma using an extraction plate having at least one gap, wherein the plasma ions pass through the at least one gap in the extraction plate to generate a focused ion beam to deposit the plurality of diamond nucleation centers; and

control the growth of a continuous diamond film from the diamond nucleation centers on the substrate by controlling at least one of a temperature around the substrate, a temperature of the plasma, a pressure around the substrate, and a concentration of the ions in the plasma.

* * * * *