

A PREPARATION CHAMBER FOR CLEANING AND REPAIR SAPPHIRE
SURFACE FOR THE EPITAXIAL GROWTH OF COMPOUND MATERIALS

Cross-Reference to Related Application

5 [0001] This application claims the benefit of priority of Singapore Patent Application No. 10202102095T, filed 2 March 2021, the content of it being hereby incorporated by reference in its entirety for all purposes.

Technical Field

10 [0002] The present disclosure relates to an apparatus configured to pre-treat a substrate for epitaxial growth of a crystalline material thereon. The present disclosure also relates to a system operable to have epitaxial growth of a crystalline material on a pre-treated substrate.

15 **Background**

[0003] Transition metal dichalcogenides (TMDCs) in monolayer or few-layer forms may be promising materials for next generation of low power electronics. A number of device operable to demonstrate mechanically exfoliated monolayer or few-layer TMDCs may have shown attractive properties such as indirect-to-direct band gap transitions, strong spin-orbit coupling and valley polarization. These may have strong implications for applications ranging from low power electronics and opto-electronics to quantum computing.

20 [0004] However, small crystal domains which tend to render undesirable prevalence of boundaries in two dimensional (2D) TMDCs degrade their physical properties. To render better TMDCs 2D films, there may be two traditional approaches. One is the growth of large grains, the other is a substrate guided (epitaxial) growth. For large grain growth, progress has been made to render grain size with a domain ranging from few μm to $\sim 100 \mu\text{m}$ domains. For epitaxial growth, this seems to be at early research stages and crystal orientation during growth is traditionally achieved at the expense of
25 reducing grain size. In other words, oriented crystal growth with large grain size should
30 be achieved but remains a difficult challenge yet to be accomplished for practical and commercial proliferation of TMDCs.

[0005] There is thus a need to provide for a solution that addresses one or more of the limitations mentioned above. The solution should at least provide for an apparatus operable to pre-treat a substrate for a TMDC to epitaxially grow thereon.

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Summary

[0006] In a first aspect, there is provided for an apparatus configured to pre-treat a substrate for epitaxial growth of a crystalline material thereon, including:

a chamber including an opening to receive the substrate for housing therein;

a gas inlet which directs a gaseous precursor into the chamber, wherein the gaseous precursor includes oxygen; and

a light source externally coupled to the chamber, wherein the light source and the chamber are configured to have the light source project ultraviolet radiation into the chamber to ionize oxygen therein into ozone for passivating the substrate, wherein the ultraviolet radiation comprises a wavelength which is sufficient to ionize the oxygen into ozone.

[0007] In another aspect, there is provided a system operable to have epitaxial growth of a crystalline material on a pre-treated substrate, including:

an apparatus described in various embodiments of the first aspect operable to provide a pre-treated substrate; and

a growth chamber arranged downstream of the apparatus to receive the pre-treated substrate directly from the apparatus, wherein the growth chamber is operable for epitaxial growth of a crystalline material on the pre-treated substrate.

Brief Description of the Drawings

10 [0008] The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the present disclosure. In the following description, various embodiments of the present disclosure are described with reference to the following drawings, in which:

15 [0009] FIG. 1 is a photo of a prototype of the preparation chamber of the present disclosure, wherein the preparation chamber is attached to a growth furnace. The photo shows the preparation chamber prototype attached to a CVD chamber (non-limiting example of the growth furnace). The dotted lines help define the area of the preparation

chamber and the location of a UV-C lamp for preparation of the substrate prior to growth stage.

[0010] FIG. 2 is a schematic showing the parts that form the preparation chamber. One part of the preparation chamber is a light source (e.g. a UV lamp operable to project
5 light in the UV-C radiation range (e.g. $\lambda=320$ to 400 nm)) on the substrate in the presence of a gas containing oxygen.

[0011] FIG. 3 shows the surface of a sapphire substrate before (top image) and after (bottom image) UV light treatment.

[0012] FIG. 4A is a schematic showing a substrate exposed to ultraviolet light (e.g.
10 UV-C) in the preparation chamber.

[0013] FIG. 4B is a schematic showing a substrate not exposed to ultraviolet light in the preparation chamber.

[0014] FIG. 4C is an optical microscopy (OM) image of a TMDC (e.g. WS_2) grown on the pre-treated substrate.

15 [0015] FIG. 4D is an OM image of a TMDC (e.g. WS_2) grown on the substrate that was not pre-treated.

[0016] FIG. 4E shows the photoluminescence spectrum of WS_2 grown on the pre-treated sapphire substrate.

20 [0017] FIG. 4F shows the photoluminescence spectrum of WS_2 grown on the sapphire substrate that was not pre-treated.

[0018] FIG. 4G shows the characterization of the crystal uniformity from two perspectives based on photoluminescence measurements over each triangular crystal. The measurements were done by rastering a laser beam (spot size $\sim$ micrometer) over the sample and then analyzing the light emission at each spot. In FIG. 4G (left image),
25 the linewidth of the light emitted from each spot was mapped out. In FIG. 4G (right image), the peak wavelength of the light emitted was mapped out. The color scales show the variations of these two properties over each crystal as well as the substrate. The actual variations excluding the substrate are in fact smaller. For the linewidth, the full-width-at-half-max (FWHM) has a variation of 1.25 out of 13.75, i.e. about $\pm 15\%$.
30 For the peak wavelength, the variation range of 618.8 to 619.5 nm represents $< \pm 0.06\%$.

[0019] FIG. 4H shows photoluminescence spectra used to characterize monolayer WS_2 displaying smaller linewidth as compared to exfoliated WS_2 , which in turn

demonstrates lower defects from the pre-treated substrate of the present disclosure. 500 denotes the spectrum for WS₂ grown on a sapphire substrate in the present preparation chamber. 502 denotes the spectrum for traditionally exfoliated WS₂.

[0020] FIG. 5A shows the epitaxial growth of WS₂ crystal grains on a sapphire substrate using a traditional method of increasing hydrogen partial pressure. The hydrogen partial pressure was increased by mixing hydrogen into argon. The image on right is an annular dark-field scanning transmission electron microscopy (ADF-STEM) image, which is magnified to show the grain boundary. It can be seen in the right image that grains at the boundary are misoriented slightly (misorientation angle of about 4°).

[0021] FIG. 5B is an ADF-STEM image showing grain boundary mismatch of 2° and 4° between segments B and C with respect to bottom segment A for WS₂ crystal grains grown on a sapphire substrate using a traditional method of increasing hydrogen partial pressure.

[0022] FIG. 5C is an ADF-STEM image showing grain boundary having holes and misorientation angle of 19° for WS₂ crystal grains grown on a sapphire substrate using a traditional method of argon gas.

[0023] FIG. 5D shows a SEM image (top image) depicting angle distributions of WS₂ crystal grains grown on a sapphire substrate using the traditional method of increased hydrogen partial pressure. FIG. 5D also shows a SEM image (bottom image) depicting angle distributions of WS₂ crystal grains grown on a sapphire substrate using the traditional method of argon gas.

[0024] FIG. 5E shows the reduction in size of MoS₂ crystal grains grown on a Al₂O₃ substrate using a traditional method of increasing sulfur supply. The grain size was compromised to improve uniform orientation of the crystal grains.

[0025] FIG. 6A shows a cross-section view of the illumination on the substrate in the preparation chamber, wherein the substrate is at a distance “d” from the light source.

[0026] FIG. 6B is a table showing the different light exposure durations at power density of 0.5 W/cm² for a particular system configuration of FIG. 6A. The table is a non-limiting example and serves to demonstrate the impact on growth orientation after UV-C treatment of the substrate for the selected duration.

[0027] FIG. 7 shows plots of aluminum (left plot) and oxygen concentration (right plot) in atomic percentage (at%) on a sapphire substrate after UV-C exposure but prior to

epitaxial growth based on XPD characterization. P1, P2 and P3 denote data taken at 3 different spots on a sapphire substrate to show there is an increase in oxygen content on the substrate surface after the UV-C exposure but prior to the epitaxial growth.

[0028] FIG. 8A is a plot of effective mass against mobility (also current density) comparing materials of silicon, tungsten diselenide (WSe₂) and tungsten disulfide (WS₂). Variation in the color scale denotes for the current density in the plot.

[0029] FIG. 8B is a plot of energy against delay highlighting the salient electrical properties of various transistors built based on few layer WS₂.

Detailed Description

[0030] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the present disclosure may be practised.

[0031] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0032] The present disclosure relates to an apparatus and a system containing the apparatus, wherein the apparatus is configured to pre-treat a substrate for epitaxial growth of a crystalline material thereon. In various embodiments, the apparatus includes a chamber which can be integrated upstream of a growth chamber for epitaxial growth of a crystalline material (e.g. transition metal dichalcogenide (TMDC)) on the substrate such that the entire process may be carried out without any exposure of the substrate (after pre-treatment) to dust or carbon residues that can occur in an uncontrolled ambient environment. The chamber may be termed herein a “preparation chamber” as the chamber prepares (i.e. pre-treats) the substrate for the epitaxial growth in the downstream growth chamber.

[0033] In various embodiments, the chamber may be coupled with a light source which provides UV treatment of the substrate in a gas mixture containing oxygen (oxygen can

be 20% or more with inert gas such as nitrogen and/or argon). The process in the chamber may be termed herein a “pre-growth step”. The epitaxial growth of a crystalline material may be carried out without modification, such as using chemical vapor deposition, metal-organic chemical vapor deposition, atomic layer deposition, etc. Advantageously, with the preparation chamber and growth chamber, epitaxial growth of the crystalline material does not compromise (reduce) the crystal grain size, but renders a more uniform orientation of the crystal grains grown on the pre-treated substrate. The present apparatus and system are applicable to a variety of substrates and crystalline materials, for example, the present apparatus and system can be suitable for any compound materials that require sapphire as a substrate for CVD crystal growth.

[0034] Through the present apparatus and system, the pre-treatment of a substrate does not require excessively high temperatures of 900°C or more. With the present apparatus and system, the pre-treatment of the substrate does not affect growth processing conditions in the growth chamber. That is to say, existing methods such as aforesaid chemical vapor deposition, metal-organic chemical vapor deposition and atomic layer deposition can be used for growing a crystalline material on the pre-treated substrate.

[0035] Details of various embodiments of the present apparatus and system, and advantages associated with the various embodiments are now described below. Where an embodiment and/or advantage has been described in the example section further hereinbelow, it shall not be iterated for brevity.

[0036] In the present disclosure, there is provided an apparatus configured to pre-treat a substrate for epitaxial growth of a crystalline material thereon. The apparatus can include a chamber that includes an opening to receive the substrate for housing therein, a gas inlet which directs a gaseous precursor into the chamber, wherein the gaseous precursor includes oxygen, and a light source externally coupled to the chamber.

[0037] In various embodiments, the gaseous precursor may be a gaseous mixture containing oxygen, or an inert gas and oxygen. Said differently, the gaseous precursor (containing oxygen) is for passivating the substrate. The inert gas may include nitrogen and/or argon. The oxygen may be present in an amount of at least 10 vol%, at least 20 vol%, at least 30 vol% of the gaseous precursor. In other words, when about 20 vol% oxygen is to be used, atmospheric air may be used. The processing duration in the chamber may depend on the oxygen content of the gaseous precursor. If less than 10

vol% is used, the duration may be undesirably longer. If the oxygen content is higher (e.g. more than 50 vol%), the process in the chamber may be more costly albeit a shorter duration.

[0038] In various embodiments, the light source and the chamber are configured to have the light source project ultraviolet radiation into the chamber to ionize oxygen therein into ozone for passivating the substrate, wherein the ultraviolet radiation has a wavelength which is sufficient to ionize the oxygen into ozone. The term “passivating” and grammatical variants thereof, in the context of the present disclosure, refer to oxidation of a substrate’s surface. Oxidation of the substrate’s surface include filling any vacant sites of the substrate’s surface with oxygen atom.

[0039] In various embodiments, the wavelength may range from 100 nm to 400 nm, 200 nm to 400 nm, 100 nm to 200 nm, 200 nm to 280 nm, 280 nm to 315 nm, 315 nm to 400 nm, 320 nm to 400 nm, etc. In certain non-limiting embodiments, the wavelength may range from 200 nm to 280 nm.

[0040] In various embodiments, the chamber may include a door coupled to the opening. The door is operably adjustable to close the opening after receiving the substrate and/or the door is operably adjustable to allow the substrate to be conveyed into the chamber through the opening.

[0041] In various embodiments, the chamber may include a movable arm therein to place the substrate received on a chuck in the chamber.

[0042] In various embodiments, the chamber may include the gas inlet and a gas outlet. The gas inlet may be connected to an inlet pump to direct the gaseous precursor into the chamber and the gas outlet may be connected to an outlet pump to deliver any gas out of the chamber.

[0043] In various embodiments, the chamber may include an exit opening coupled with an exit door for the substrate to be conveyed out of chamber. The exit door is operably adjustable to close the exit opening after the substrate is conveyed out of the chamber and/or the exit door is operably adjustable to allow the substrate to be conveyed out of the chamber through the exit opening.

[0044] In various embodiments, the light source may be arranged at a distance from where the substrate is housed in the chamber. In various embodiments, the light source may be positioned vertically above and at a distance from the substrate.

[0045] In various embodiments, the chamber may have a transparent portion proximal to the light source. The light source may be arranged to project light downward onto where the substrate is housed in the chamber through the transparent portion. In certain non-limiting embodiments, the light source may be coupled to a surface defining a wall of the chamber, wherein the surface is transparent.

[0046] In various embodiments, the chamber is operable at atmospheric pressure for passivating the substrate.

[0047] In various embodiments, the crystalline material includes a transition metal dichalcogenide. The transition metal dichalcogenide may include tungsten disulfide, tungsten diselenide, tungsten ditelluride, molybdenum sulfide, molybdenum diselenide, or molybdenum ditelluride.

[0048] In various embodiments, the substrate may include sapphire or is a sapphire substrate. A sapphire substrate includes or may consist of aluminum oxide (Al_2O_3).

[0049] The present disclosure also relates to a system operable to have epitaxial growth of a crystalline material on a pre-treated substrate. Embodiments and advantages described in various embodiments of the first aspect regarding the apparatus can be analogously valid for the present system subsequently described herein, and vice versa. Where the various embodiments and advantages have already been described above and in the example section demonstrated further hereinbelow, they shall not be iterated for brevity.

[0050] The system may include an apparatus described in various embodiments of the first aspect wherein the apparatus is operable to provide a pre-treated substrate, and the system may include a growth chamber arranged downstream of the apparatus to receive the pre-treated substrate directly from the apparatus, wherein the growth chamber is operable for epitaxial growth of a crystalline material on the pre-treated substrate.

[0051] The pre-treated substrate may include sapphire or is a sapphire substrate. The pre-treated substrate refers to a substrate that has been processed in the apparatus described in various embodiments of the first aspect.

[0052] In various embodiments, the apparatus may include the chamber with the exit opening for the pre-treated substrate to be conveyed out therefrom and the growth chamber may include an entrance opening to receive the pre-treated substrate, wherein

the exit opening and the entrance opening may be connected with a closed channel in which the pre-treated substrate is conveyed through.

[0053] In various embodiments, the growth chamber may include or may be a chemical vapor deposition chamber, metal-organic chemical vapor deposition chamber, or an atomic layer deposition chamber.

[0054] The word “substantially” does not exclude “completely” e.g. a composition which is “substantially free” from Y may be completely free from Y. Where necessary, the word “substantially” may be omitted from the definition of the present disclosure.

[0055] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0056] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance.

[0057] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0058] Unless specified otherwise, the terms "comprising" and "comprise", and grammatical variants thereof, are intended to represent "open" or "inclusive" language such that they include recited elements but also permit inclusion of additional, unrecited elements.

Examples

[0059] The present disclosure relates to an apparatus and a system containing the apparatus. The apparatus includes a uniquely developed chamber (herein interchangeably termed “preparation chamber”) configured to pre-treat a substrate prior to growth (e.g. via chemical vapour deposition (CVD)) of transition metal dichalcogenides (TMDCs). The chamber is configured to at least (1) prepare a surface of substrate to allow the growth of TMDCs with a preferential orientation and (2) clean the surface from organic/dust residues prior to growth of the TMDCs.

[0060] FIG. 1 is a photo of a non-limiting example of the preparation chamber prototype coupled to a CVD chamber of the present disclosure. The dotted line defines the area of the preparation chamber and the location of the UV-C lamp (for preparation of the substrate prior to growth of the TMDC) from the CVD chamber.

[0061] The present apparatus and system are described in further details, by way of non-limiting examples, as set forth below.

[0062] Example 1: Schematic of Present System and Preparation Chamber

[0063] FIG. 2 is a schematic illustrating a non-limiting example of the present system 100 including the apparatus 110 and a growth chamber 120. FIG. 2 also depicts various parts of the apparatus 110 (see magnified image on right).

[0064] In FIG. 2, it can be seen that the apparatus 110 has a preparation chamber 20 (i.e. chamber 20 for brevity) for housing a substrate to be treated therein. The preparation chamber 20 (and understandably the apparatus 110) has an opening 22 to receive a substrate to be conveyed therein (depicted by arrow 10). While not shown, the opening 22 can have a door coupled thereto, which is operably adjustable such that the preparation chamber 20 becomes a closed chamber after the substrate is received and housed therein for processing. A closed chamber affords a controlled environment for pre-treating the substrate. In other words, the door is operable to (i) open the preparation chamber 20 for receiving the substrate (e.g. door is operably positioned such that the opening 22 can receive the substrate) and (ii) shut the preparation chamber 20 after receiving the substrate (e.g. door is operably positioned such that the opening 22 does not allow a substrate to be conveyed in). The preparation chamber 20 has an exit opening (not shown) for the substrate to be conveyed out (depicted by arrow 12). The exit opening may have an exit door (not shown) coupled thereto, which is operably adjustable for opening (for substrate to be conveyed out) and shutting (after substrate is conveyed out) the preparation chamber 20. The exit door can be operably independent of the door at opening 22 or co-operable (open and close together) with the door at opening 22. The preparation chamber 20 may have a moveable arm (not shown) operable to convey the substrate in and out. Any other conveying means that can transfer a substrate in and out of the preparation chamber 20 may be used. In the preparation chamber 20, there may be a chuck (not shown) which the received substrate rests on. That is to say, the moveable arm may convey the substrate received at opening 22 and place the substrate on the chuck. The chuck may be an electrostatic chuck (e.g. secures the substrate by electrostatic attraction).

[0065] The exit opening leads directly to the growth chamber 120. Said differently, any intervening process units are absent between preparation chamber 20 (and

understandably the apparatus 110) and growth chamber 120 such that a substrate conveyed out from the preparation chamber 20 (and understandably the apparatus 110) gets transferred directly to the growth chamber 120. There may be a closed channel in which the processed (i.e. pre-treated) substrate is conveyed from the preparation chamber 20 (and understandably the apparatus 110) to the growth chamber 120. The closed channel minimizes and/or avoids the pre-treated substrate from being exposed to atmosphere. Alternatively, if a pod for housing and transferring a substrate is used (e.g. front opening unified pod or front opening universal pod), the closed channel may not be needed. The pod can be a portable enclosure for housing a substrate so that the substrate can be transferred from the preparation chamber 20 (and understandably the apparatus 110) to the growth chamber 120 without exposing the substrate to atmosphere during the transfer. The pod may have a front door that can be opened (for receiving a substrate or removing a substrate therefrom) and closed (during transport of the substrate). The front door of the pod may be operably positioned at (e.g. aligned with) the preparation chamber 20 and at the growth chamber 120 for transfer of the substrate out and in.

[0066] The preparation chamber 20 may have a gas inlet 26 and a gas outlet 28. Each of the gas inlet 26 and gas outlet 28 may be connected to a gas pump (for delivering gas in or out, respectively) via a hose or pipe (not shown). The gas inlet 26 directs a gaseous precursor into the chamber 20 (depicted by arrow 14) and the gas outlet 28 directs gas out (depicted by arrow 16), i.e. the gas inlet 26 and gas outlet 28 facilitate gas exchange in the preparation chamber 20. The gaseous precursor may be used to clean a surface of the substrate. The gaseous precursor may also be used to passivate the surface. The gaseous precursor may contain oxygen. The oxygen may be present in an amount of at least 10 vol%, at least 20 vol%, or at least 30 vol%, etc., of the gaseous precursor.

[0067] The preparation chamber 20 may include a light source 30 externally coupled. As a non-limiting example shown in FIG. 2, the preparation chamber 20 may have a transparent window 32 configured to have light from the externally coupled light source 30 projected into the chamber 20. There may be a seal 24 to prevent the gaseous precursor from escaping between the transparent window 32 and chamber 20. In certain non-limiting examples, the chamber 20 need not have a rectangular structure as shown in FIG. 2. Instead, the chamber 20 may have a tubular structure. In certain non-limiting

instances, the tubular structure may be entirely transparent or has a surface which the light source 30 is coupled to that is transparent, and in such instances, the window 32 may form the surface and seal 24 is then not needed. The light source 30 and the preparation chamber 20 are configured to have the light source 30 project ultraviolet radiation into the preparation chamber 20 to ionize the gaseous precursor (e.g. oxygen) therein into ozone for pre-treating (e.g. cleaning and/or passivating) the substrate. In various non-limiting examples, the light source 30 may be configured to shine light on the substrate in the presence of an oxygen-containing gas. The ultraviolet radiation may have a wavelength sufficient to ionize the oxygen into ozone. The wavelength may be in the range of 100 nm to 400 nm, 100 nm to 200 nm, 200 nm to 280 nm, 280 nm to 315 nm, 315 nm to 400 nm, etc. The ultraviolet radiation may be ultraviolet-C (UV-C) in various non-limiting examples discussed in the present disclosure. In non-limiting examples, the light source 30 may be a UV lamp operable in the UV-C radiation range or the light may have a wavelength of 320 nm to 400 nm. In non-limiting examples, the window 32 may be selectively and optically pervious to UV-C. The cleaning and passivation processes are discussed in example 2 below. After pre-treating the substrate, the substrate is conveyed out of the preparation chamber 20 to be transferred to the growth chamber 120.

[0068] The growth chamber 120 is arranged downstream of the preparation chamber 20 (and understandably downstream of the apparatus 110). The growth chamber 120 receives a pre-treated substrate directly from the preparation chamber 20. As mentioned above and observable in FIG. 2, there is no other intervening process units between the preparation chamber 20 (and understandably the apparatus 110) and the growth chamber 120, such that the substrate pre-treated in the preparation chamber 20 can be conveyed straight to the growth chamber 120. The growth chamber 120 is operable for epitaxial (oriented) growth of a crystalline material (e.g. a TMDC) on the pre-treated substrate. Epitaxial growth observations and results arising from the effect of pre-treatment in the apparatus 110 is discussed in example 3.

[0069] Example 2: Surface of Pre-Treated Substrate

[0070] As mentioned above, light (e.g. in the UV-C range) can ionize the oxygen gas in the preparation chamber, which cleans a surface of a substrate (e.g. sapphire substrate) and passivate the oxygen vacancies. This is depicted in FIG. 3, which

illustrates the process. The arrows in FIG. 3 (top image) schematically show the oxygen vacancies and carbon contamination that are present in the as-received sapphire substrate.

[0071] As can be seen in FIG. 3 (top and bottom images), for example, hydrogen, carbon and hydrocarbon may be present on the surface of substrate. With UV light, oxygen present in the preparation chamber is ionized into ozone and reacts away with the hydrogen and carbon, forming vacant sites on the substrate's surface. The vacant sites get passivated with oxygen as the substrate's surface (e.g. sapphire) oxidizes, i.e. the surface of the substrate is uniformly passivated (oxidized).

10 **[0072] Example 3: Orientation and Size of Crystal Grown on Pre-Treated Substrate**

[0073] The cleaning and passivation of the substrate is advantageous to render the epitaxial growth with large crystal domains (size) of 50 μm or more and also a high degree of oriented growth. FIG. 4A to 4F demonstrate for the effect of TMDC growth with UV treatment (see FIG. 4A, 4C, 4E) and without UV treatment (FIG. 4B, 4D, 4F).

15 [0074] By pre-treating a substrate in the present preparation chamber, which is configured with the light source (e.g. UV light source) and operable to have an oxygen flow to sustain a desirable surface oxidation and cleaning process, high quality epitaxial growth is rendered as evidenced by a general reduction of the photoluminescence (PL) linewidth. The epitaxial growth occurred with more uniform crystal orientation without compromising (i.e. reducing) the grain size.

[0075] On the other hand, traditional methods to render oriented growth may include (1) increase H_2 partial pressure during growth or (2) increase of sulfur supply during growth. The methods do not involve the preparation chamber described herein, wherein the preparation chamber is equipped with a light source operable to ionize oxygen for cleaning and/or repairing a surface of a substrate (e.g. sapphire). In addition, the H_2 and sulfur pressure control methods undesirably exert a significant influence on the growth process by reducing the grain size.

20 [0076] For instance, in FIG. 5A, when WS_2 crystal grains grow on a sapphire substrate in the presence of hydrogen (i.e. increase hydrogen partial pressure, e.g. introducing hydrogen to an inert gas such as argon to form a mixture of hydrogen and argon), a boundary is formed between the neighbouring segments of crystal grains that grew. The

boundary is formed by “stitching”, wherein two crystals may start growing at separate locations but the two crystals come into contact when the two crystals grow large enough and the contact point is referred to as a “stitch” and hence the term “stitching” describes such a boundary contact developed from crystal growth. However, the stitching is still susceptible to defects, for example, crystal grains at boundary are not aligned (see FIG. 5B) and/or holes may arise. In FIG. 5A, even with introduction of hydrogen to argon to grow the crystal grains, one-dimensional (1D) dislocation with small point defects (dislocation cores) are still observed. In FIG. 5B, it can be seen that orientation of crystal grains (on a sapphire substrate) at the boundary between segments B and C are not aligned, i.e. crystals grains in segments B and C at boundary are misoriented at an angle of 2° and 4° with respect to bottom segment A. In FIG. 5C, using argon absent of hydrogen, holes are observed at the boundary and there is a misorientation angle of 19° between the crystal grains (on a sapphire substrate). In FIG. 5D, comparing between top image (a) and bottom image (b), it can be seen that increase in hydrogen partial pressure with introduction of hydrogen to argon render a more uniform orientations of the crystals grains on a sapphire substrate (top image) whereas crystal grains were more misoriented using argon absent of hydrogen (see bottom image). Despite the improved orientation of crystal grains with hydrogen, it can be seen that the grain sizes were undesirably reduced (compare top image to bottom image in FIG. 5D).

[0077] For the other traditional method involving an increase of sulfur supply during growth, it can be seen that grain size were undesirably reduced as well (FIG. 5E). As can be seen, the size of MoS₂ crystal grains becomes smaller with increase of sulfur supply.

[0078] As demonstrated above, traditional methods render the TMDC crystal grain size smaller, which potentially in turn gives rise to misalignment at boundary. The smaller grain size may also render more defects (e.g. holes). Through use of the present apparatus and system, TMDC crystals grown on a pre-treated substrate do not have their size reduced and achieves a more uniform orientation with improved grain size.

[0079] **Example 4: Effect of Light Exposure Duration and Light Power Density**

[0080] FIG. 6A shows a cross-section view of the preparation chamber wherein UV light is projected on the substrate housed in the preparation chamber. In various non-

limiting examples, the distance between the light source and substrate (denoted by “d”) was fixed to 5 cm and variation in light exposure duration (see FIG. 6B) was investigated until oriented growth was observed. In the prototype preparation chamber, oxygen in a concentration (e.g. about 20%) at atmospheric pressure was tested, and power density of the UV lamp was maintained constant at 0.5 W/cm^2 . It should be noted that changing d and/or fixing the exposure time were explored to vary the pre-treatment of the substrate’s surface. If d is doubled, the UV intensity may be 4 times less and the rate of treatment of the substrate of in the preparation chamber may decrease (this may be suitable for applications that do not require a high rate of treatment).

[0081] The power density of the light source can be varied. For example, it was observed that the sapphire substrate’s surface was cleaned/repared to render oriented growth when the average UV energy density imparted to the surface is, for example, $\geq 0.5 \text{ W/cm}^2$ for a duration of 20 mins ($0.5 \text{ W/cm}^2 \times 1200 \text{ s} = 600 \text{ J/cm}^2$). Similarly, increasing the UV power density helps accelerate treatment of the substrate in the preparation chamber. Once the surface of the substrate is cleaned/passivated, the condition of the surface of the substrate does not changed significantly under continued exposure to the UV light in presence of the oxygen.

[0082] Two sources of different UV wavelength were tested: (i) UV-C range (200 - 280 nm) and (ii) UV-B range (280 – 320 nm). Using the UV-C lamp, crystal orientation was clearly achieved. In the case of UV-B lamp, no clear sign of crystal orientation was achieved.

[0083] Example 5: Commercial and Potential Applications

[0084] The present apparatus and system are advantageous as both include a preparation chamber, which is configured and operable to pre-treat a substrate for subsequently forming a crystalline TMDC material thereon. The apparatus and system are not limited to forming a TMDC material, but can be used to pre-treat any substrate suitable for growing other crystalline materials thereon. The preparation chamber pre-treats the substrate, which is in turn advantageous for inducing epitaxial growth of a crystalline material on the clean and passivated substrate.

[0085] The present apparatus and system can be conveniently integrated with any other semiconductor processing steps and units (e.g. a chemical vapor deposition unit, a metal-organic chemical vapor deposition unit, atomic layer deposition process, etc.).

[0086] While the present disclosure has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the present disclosure as defined by the appended claims. The
5 scope of the present disclosure is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. An apparatus configured to pre-treat a substrate for epitaxial growth of a crystalline material thereon, comprising:
 - a chamber comprising an opening to receive the substrate for housing therein;
 - a gas inlet which directs a gaseous precursor into the chamber, wherein the gaseous precursor comprises oxygen; and
 - a light source externally coupled to the chamber, wherein the light source and the chamber are configured to have the light source project ultraviolet radiation into the chamber to ionize oxygen therein into ozone for passivating the substrate, wherein the ultraviolet radiation comprises a wavelength which is sufficient to ionize the oxygen into ozone.
2. The apparatus of claim 1, wherein the wavelength ranges from 100 nm to 400 nm.
3. The apparatus of claim 1 or 2, wherein the wavelength ranges from 200 nm to 280 nm.
4. The apparatus of any one of claims 1 to 3, wherein the chamber comprises a door coupled to the opening, wherein the door is operably adjustable to close the opening after receiving the substrate and/or allow the substrate to be conveyed into the chamber through the opening.
5. The apparatus of any one of claims 1 to 4, wherein the chamber comprises a movable arm therein to place the substrate received on a chuck in the chamber.
6. The apparatus of any one of claims 1 to 5, wherein the chamber comprises the gas inlet and a gas outlet, wherein the gas inlet is connected to an inlet pump to direct the gaseous precursor into the chamber and the gas outlet is connected to an outlet pump to deliver any gas out of the chamber.

7. The apparatus of any one of claims 1 to 6, wherein the chamber comprises an exit opening coupled with an exit door for the substrate to be conveyed out of chamber, wherein the exit door is operably adjustable to close the exit opening after the substrate is conveyed out of the chamber and/or allow the substrate to be conveyed out of the chamber through the exit opening.
8. The apparatus of any one of claims 1 to 7, wherein the light source is arranged at a distance from where the substrate is housed in the chamber.
9. The apparatus of any one of claims 1 to 8, wherein the chamber has a transparent portion proximal to the light source, wherein the light source is arranged to project light downward onto where the substrate is housed in the chamber through the transparent portion.
10. The apparatus of any one of claims 1 to 9, wherein the light source is coupled to a surface defining a wall of the chamber, wherein the surface is transparent.
11. The apparatus of any one of claims 1 to 10, wherein the chamber is operable at atmospheric pressure for passivating the substrate.
12. The apparatus of any one of claims 1 to 11, wherein the crystalline material comprises a transition metal dichalcogenide.
13. The apparatus of claim 12, wherein the transition metal dichalcogenide comprises tungsten disulfide, tungsten diselenide, tungsten ditelluride, molybdenum disulfide, molybdenum diselenide, or molybdenum ditelluride.
14. The apparatus of any one of claims 1 to 13, wherein the substrate is a sapphire substrate.

15. A system operable to have epitaxial growth of a crystalline material on a pre-treated substrate, comprising:

an apparatus of any one of claims 1 to 14 operable to provide a pre-treated substrate; and

a growth chamber arranged downstream of the apparatus to receive the pre-treated substrate directly from the apparatus, wherein the growth chamber is operable for epitaxial growth of a crystalline material on the pre-treated substrate.

16. The system of claim 15, wherein the pre-treated substrate is a sapphire substrate.

17. The system of claim 15 or 16, wherein the apparatus comprises a chamber with an exit opening for the pre-treated substrate to be conveyed out therefrom and the growth chamber comprises an entrance opening to receive the pre-treated substrate, wherein the exit opening and the entrance opening are connected with a closed channel in which the pre-treated substrate is conveyed through.

18. The system of any one of claims 15 to 17, wherein the growth chamber comprises a chemical vapor deposition chamber, metal-organic chemical vapor deposition chamber, or an atomic layer deposition chamber.