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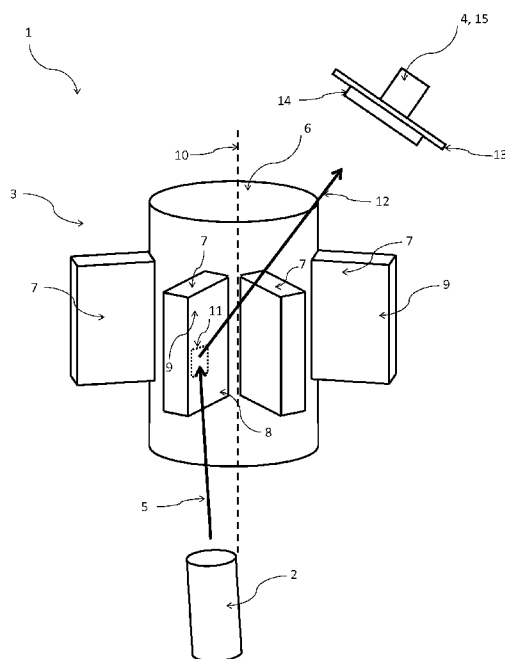


Fig. 3

(57) Abstract: A system (1) is disclosed, comprising a gas source (2), a rotor (3), at least one positioning device (4) and a target holder (13). The gas source is configured to provide a source jet of gas (5) towards the rotor. The rotor is configured to change the velocity of the source jet of gas (5) to provide an accelerated jet of gas (12). The at least one positioning device (4) is configured to control relative position and/or orientation of the accelerated jet of gas (12) from the rotor (3) and the target holder (13).

ROTOR GAS ACCELERATOR SYSTEM AND METHODS

Field of the invention

The invention relates to rotor gas accelerator systems and methods. In particular, the invention relates to rotor gas accelerator systems and methods having applications in thin film processing.

Background of the invention

Currently thin film processes typically require a high temperature step to form a high quality and relatively defect free phase. Indeed, the crystallization process of a material usually requires rather high temperature. However for thin films on a substrate the interactions with the substrate are a limiting factor as diffusion between film and substrate must be avoided as much as possible. Often it is impossible to reconcile these different requirements. For instance for the growth of materials on polymer substrates it is clear that the maximum growth temperatures cannot exceed the glass transition temperature of the polymer. Also for the growth of films on typical semiconductor substrates, the formation of intermediary phases such as SiO₂ on Si cannot be avoided if the substrate temperature becomes too high.

To circumvent these issues a number of processes have been developed in the art such as the rapid thermal annealing process that anneal the film in a short time after the film growth. However in that case still the entire system consisting of thin film and substrate are brought to high temperature and it is the fact that "rapid processing" occurs, i.e. processing within a number of seconds, that limits the diffusion damage. Another method currently used in the art is to apply a "direct" or a "remote" plasma to the growing front. This plasma is usually created by a DC, RF, Microwave or electron cyclotron resonance (ECR) type of discharge whereby a whole range of active species is created such as atomic elements, excited atoms and molecules as well as electrons and different ions. When they bombard the surface, inevitably this will also lead to a heating of the substrate surface layer or the thin film growing layer. However the energetic spectral distribution of these species is usually very large mostly including sputtering of surface atoms, which is not gentle.

The main shortcomings in the state of the art are twofold. Since the thermal budget during the film formation is limited it is impossible to make the film of good structural quality. This will limit the overall performance of the thin film on all fronts. The second main shortcoming is related to the diffusion issues and the large set of "complicated" defects that arise as a consequence thereof. For instance in the case of a gate stack, the diffusion of semiconductor atoms (from Si, Ge, GaAs or InGaAs) into the oxide always leads to poor electrical behavior. Vice versa the diffusion of metallic, nitrogen or oxide species into the semiconductor also gives rise to unwanted defects into the semiconductor.

While the sputtering / plasma methods are relatively simple, they also have a number of disadvantages. For instance, in the case of sputtering, energetic ions of different polarity and charge are emitted and can cause significant damage to the substrate and film.

This is only partially compensated by making use of a sufficiently high background pressure where these species undergo enough collisions and lose their energy.

An additional shortcoming in the state of the art is that thermal stability is critical when deposition takes place on unusual materials such as plastic or wood, etc. In those cases it is not possible to heat up the substrate to a high temperature and this restricts seriously the amount of films that can be well integrated with those organic substances.

Therefore there is a need for more gentle methods and tools to grow, etch and/or anneal thin films.

Summary of the invention

It is an object of the present invention to provide good methods and systems for assisting in thin film processing.

It is an advantage of embodiments of the present invention that good methods and systems are provided for transferring energy to a target using a gas flow.

It is an advantage of embodiments of the present invention that good methods and systems are provided for controlling the energy transferred to a target, using a gas flow.

According to a first aspect of the present invention, there is provided a system comprising a gas source, a rotor, at least one positioning device and a target holder, wherein the gas source is configured to provide a source jet of gas towards the rotor, wherein the rotor is configured to change the velocity of the source jet of gas to provide an accelerated jet of gas, and wherein the at least one positioning device is configured to control relative position and/or orientation of the accelerated jet of gas from the rotor and the target holder.

Where in embodiments of the present invention reference is made to acceleration e.g. towards an accelerated jet, reference is made to acceleration induced by gas species hitting the rotor. The accelerated jet of gas may be defined as the gas plume between the rotor and the target holder. Within this gas plume which may have a fixed position, the gas particles are accelerated.

The at least one positioning device may be configured for controlling a relative position and/or orientation between at least two of the target holder, the rotor and the gas source, such that the relative position and/or orientation is controlled of where the accelerated jet of gas impinges on the target holder.

The system may comprise a chopper disposed between the gas source and the rotor.

The system may comprise a chopper disposed between the rotor and the target holder.

The gas source may be configured to provide a source jet of gas which is laminar. The gas source may be configured to provide a source jet of gas which is turbulent.

The gas source may comprise a temperature controller configured to control a temperature of the source gas.

- 5 The system may comprise a rotor temperature controller configured to control a temperature of the rotor.

The system may comprise a rotor controller configured to control rotation speed of the rotor.

The system may comprise a positioning controller configured to control the positioning device.

- 10 The source jet of gas may comprise reactive elements. The source jet of gas may comprise inert elements. The source jet of gas may comprise neutral elements.

The target holder may support a target and the positioning device may be configured to direct the accelerated jet of gas towards the target. The target may comprise a substrate. The substrate may comprise a single material. The substrate may comprise a base layer and at least one thin film layer on the base layer.

- 15 The system may be adapted for rotating the target holder during the provision of the source jet of gas in order to improve or ensure homogeneity of the impingement of the accelerated gas jet on the target holder or on a substrate positioned in the target holder. Rotating of the target holder may comprise providing a rotation with a rotation axis perpendicular to the substrate.

The target may comprise a specified position on a substrate.

- 20 According to a second aspect of the present invention there is provided use of a system according to the first aspect in an annealing process.

According to a third aspect of the present invention there is provided use of a system according to the first aspect in a thin film cleaning process.

- 25 According to a fourth aspect of the present invention there is provided use of a system according to the first aspect in a thin film deposition process.

- According to a fifth aspect of the present invention there is provided a method of treating a substrate, the method comprising providing a system according to the first aspect; providing the substrate in the target holder; and directing the accelerated jet of gas towards the substrate using the positioning
30 device.

The accelerated jet of gas may be directed towards a defect site on the substrate.

The method may be an etching method.

The method may be a substrate cleaning method.

The method may further comprise further comprising a deposition step for depositing sample material for a thin film on the substrate. A lithography mask may be provided on a surface of the substrate. The lithography mask may comprise a photoresist.

Particular and preferred aspects of the invention are set out in the accompanying independent and dependent claims. Features from the dependent claims may be combined with features of the independent claims and with features of other dependent claims as appropriate and not merely as explicitly set out in the claims.

Brief Description of the Drawings

Certain embodiments of the present invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 illustrates the distribution of molecular speeds of Nitrogen gas molecules at a range of temperatures from 300 K to 1200 K;

Figure 2 illustrates the distribution of energy density as a function of wavelength for a black body radiator at different temperatures;

Figure 3 is a schematic view of a rotor accelerator system according to embodiments of the present invention;

Figure 4 is a schematic view of a rotor blade and a gas molecule impinging on the rotor blade;

Figure 5 is a logarithmic plot of the kinetic energy of various species of gas as a function of the revolutions per minute of a rotor, with an impingement point on the blade located at 6 cm from the axis of rotation of the rotor;

Figure 6 is a linear plot of the kinetic energy of various species of gas as a function of the distance of the impingement point of a gas molecule on a rotating blade from the axis of rotation of the rotor (the radius) for a rotation speed of 500,000RPM;

Figure 7 is a linear plot of the velocity of a point on a rotor blade as a function of the distance of the impingement point of a gas molecule on a rotating blade from the axis of rotation of the rotor (the radius), for various rotor rotation speeds;

Figure 8 is a schematic cross-section of a rotor cylinder and rotor blade as can be used in embodiments of the present invention;

Figure 9 is a plan view of a system according to embodiments of the present invention which includes one or more choppers.

Figure 10 is a schematic perspective view of a system according to embodiments of the present invention wherein the positioning device is a platform which supports the rotor and gas source.

The drawings are only schematic and are non-limiting. In the drawings, the size of some of the elements may be exaggerated and not drawn on scale for illustrative purposes.

Any reference signs in the claims shall not be construed as limiting the scope. In the different drawings, the same reference signs refer to the same or analogous elements.

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Detailed Description of Certain Embodiments

It is to be noticed that the term “comprising”, used in the claims, should not be interpreted as being restricted to the means listed thereafter; it does not exclude other elements or steps. It is thus to be interpreted as specifying the presence of the stated features, integers, steps or components as referred to, but does not preclude the presence or addition of one or more other features, integers, steps or components, or groups thereof. Thus, the scope of the expression “a device comprising means A and B” should not be limited to devices consisting only of components A and B. It means that with respect to the present invention, the only relevant components of the device are A and B.

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Reference throughout this specification to “one embodiment” or “an embodiment” means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, appearances of the phrases “in one embodiment” or “in an embodiment” in various places throughout this specification are not necessarily all referring to the same embodiment, but may. Furthermore, the particular features, structures or characteristics may be combined in any suitable manner, as would be apparent to one of ordinary skill in the art from this disclosure, in one or more embodiments.

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Similarly it should be appreciated that in the description of exemplary embodiments of the invention, various features of the invention are sometimes grouped together in a single embodiment, figure, or description thereof for the purpose of streamlining the disclosure and aiding in the understanding of one or more of the various inventive aspects. This method of disclosure, however, is not to be interpreted as reflecting an intention that the claimed invention requires more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive aspects lie in less than all features of a single foregoing disclosed embodiment. Thus, the claims following the detailed description are hereby expressly incorporated into this detailed description, with each claim standing on its own as a separate embodiment of this invention.

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Furthermore, while some embodiments described herein include some but not other features included in other embodiments, combinations of features of different embodiments are meant to be within the scope of the invention, and form different embodiments, as would be understood by those in the art. For example, in the following claims, any of the claimed embodiments can be used in any combination.

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In the description provided herein, numerous specific details are set forth. However, it is understood that embodiments of the invention may be practiced without these specific details. In other instances, well-known methods, structures and techniques have not been shown in detail in order not to obscure an understanding of this description.

- 5 In the following, where a substrate is referred to, a substrate may comprise a single material, for example a single layer of material, which may be for example a wafer. A substrate may comprise a base layer and one or more over- or under-lying layers on the substrate. A substrate may comprise a stack, for example a multilayer stack. A substrate may comprise one or more layers having etched or patterned features.
- 10 Heating by using a hot gas stream or through a radiative heating filament or black body provides a heat source having an energy or velocity distribution which follows Maxwell-Boltzmann statistics. That is, for a given gas at a fixed temperature, a relatively wide range of velocities of the gas particles (and thus kinetic energies) is present. Referring to Figure 1, the distribution of molecular speeds for Nitrogen gas at various temperatures between 300K and 1200K is shown. As the temperature
- 15 increases, the width of the velocity distribution becomes larger, and the maximum of the velocity distribution shifts to higher energies. Correspondingly, there is a broad distribution of kinetic energies present in the gas and thus a broad range of energies transferred to a substrate of a growing film. This is in contrast to what is often needed during growth and annealing. In many cases, for instance when a defect in a thin film is required to be annealed out, only a very specific energy within a narrow
- 20 energy range (illustrated by the corresponding velocity range X in Figure 1) is needed in order to move the atom (or defect) from, for example, an interstitial site to a lattice site in a crystal. Consequently, a large portion of the energy transferred through collisions between a hot gas and a substrate is wasted because the energy of the gas molecules involved in the collisions is either too low or too high. This can also contribute to unnecessary and/or undesired heating of the substrate.
- 25 A similar reasoning is made where heating is provided using radiation from, for instance, a black body radiator. Figure 2 illustrates the energy density radiated from a black body at different temperatures from 800K to 1000K. Again a relatively wide distribution of energies is observed, with the maximum energy increasing to higher energies as the temperature of the black body is increased. It is noted that in terms of energy, for the horizontal axis in Figure 1, a larger velocity corresponds to a larger energy,
- 30 whereas for the horizontal axis in Figure 2, a larger wavelength corresponds to a lower energy. The energy within a narrow energy range required to anneal out a defect type is shown as region Y. It is seen that a large portion of the radiated energy is either too small or too large to allow an efficient process, that is, the energy is wasted and can contribute to unnecessary and/or undesired heating of the substrate.

In typical growth or annealing processes, it is preferred that the desired results are obtained at as low temperature as possible. The desired results depend on the thin film and its application and may include, for example, layer thickness, layer smoothness, homogeneity of crystal structure, grain size, epitaxial orientation, compositional uniformity, activation of dopants, passivation of defects, electrical properties, optical properties, magnetic properties. In some applications a small diffusion between layers may be preferred – for instance in the case of metallisation layers on semiconductors where often silicides for instance are created at an interface. Consequently, a temperature of a gas or radiation source used to heat the substrate or target is chosen such that the high energy tail of the energy distribution overlaps to some extent with the required energy scale. However, it is then also clear that a large portion of the energy distribution of the radiation source or gas is too low to have any useful effect in providing the desired results and is consequently wasted through substrate heating.

Furthermore, if a too high energy is used, only a portion of the incident energy serves to anneal out a defect, while the remaining energy is wasted. Therefore, it is desired to provide methods and apparatus to perform thin film growth and annealing experiments while keeping the overall temperature of the sample low. Embodiments of the present invention allow to do this in a well-controlled manner.

Instead of heating the entire substrate, according to embodiments of the present invention it is desired to only heat the top surface of the growing thin film to a desired temperature (for example, a temperature required to anneal a defect). The remainder of the substrate may remain cold or may be heated to a lower, "safe" temperature at which interactions can be limited within the limits provided by thermal conductivity of the corresponding materials.

According to embodiments of the present invention, systems and methods are provided for supplying a gaseous species to a target by accelerating the gas using a high speed rotating motor and blade structure. The present invention may for example be used for providing heating to a substrate; decomposing a metal-organic compound on a substrate in, for example, atomic layer deposition or chemical layer deposition; in sputtering processes and in etching processes.

The gas supplied may be a substantially neutral gas, which can allow that production of defects due to the bombardment of a substrate by charged species is reduced. "Substantially neutral" means a fraction of charged and/or radical species may be present in the gas provided that the interaction of such charged and/or radical species with the substrate or thin film does not lead to a significant portion of relevant defects in the film or substrate. A relevant defect is for instance a vacancy or an interstitial or a dislocation or a domain boundary or a clustering, a segregation etc. For example, in a high performance Si MOSFET, defect densities are preferably below $1 / \text{cm}^2$, however this threshold

can vary depending on the type of defect. Since these defects can affect the carrier mobility and the long term reliability they should preferably be avoided. However, in some applications a larger proportion of defects can be easily tolerated. In the case of a semiconductor device, any defect, vacancy, interstitial, etc, can lead to a defect energy level in the band structure. If the position of that energy level is such that an applied potential to the device causes charging and discharging of carriers at that energy level then this is not a tolerable defect, as it would affect carrier mobility as a scattering center or a reliability issue. Defects in oxides would be similarly undesirable, defects in a ferroelectric material would be sensitive to variation in the dipole environment, defects in a ferromagnetic material would be sensitive to interruption in the magnetic orientation, and are preferably avoided. The notion of relevant defects will then depend on the desired use of the film. For example, if a thin film material is very sensitive to charged defects, then the allowed portion of charged radical species will be relatively low as a proportion of the accelerated gas jet. It is noted that a fraction of gas molecules accelerated by the system may become radicals (for example, converted from O₂ to O) and may become ionized, in dependence on the amount of energy transferred. The higher the rotation speed and energy transferred the higher the fraction of ionic species and radicals. The fraction of ionic species and radicals may become a majority fraction in some embodiments, that is, greater than 50% and this can in some embodiments be a preferred feature.

Referring to Figure 3, a system 1 is shown according to an embodiment of the present invention. The system 1 comprises a gas source 2, a rotor 3, and a positioning device 4.

In the present example, the rotor 3 comprises a central cylinder 6 and at least one blade 7. For example, in embodiments of the invention the rotor 3 comprises one, two, three, four or more blades 7. In the following a single blade will be referred to, however it will be understood that the properties, characteristics, and behavior of any further blades 7 which may be comprised in rotor 3 will be substantially the same as those of the single described blade 7.

The blade 7 has a first end 8 which is proximal to the cylinder 6 and is attached to the cylinder 6. The at least one blade 7 has a second end 9 opposite the first end 8. The second end 9 is distal to the cylinder 6, that is, the second end 9 is further from the cylinder 6 than the first end 8.

The rotor 3 is configured to rotate about a central axis 10 of the cylinder 6.

It will be clear for the person skilled in the art that also other configurations of a rotor 3 can be used, provided the rotor 3 results in the provision of at least one rotating blade 7.

The gas source 2 is configured to provide a source jet of gas 5 towards the rotor 3. In preferred embodiments of the invention, the gas source is configured to provide a laminar gas jet. The gas source 2 is preferably configured to provide a source jet of gas 5 towards the rotor 3 such that at least a portion of the source jet of gas 5 impinges on at least a portion 11 of at least one blade 7. The portion

11 of the blade 7 is preferably proximal to the second end 9, that is, located at a position which is relatively further from the rotor axis 6.

The source jet of gas 5 has an initial velocity vector v_i before contact with the at least one blade 7. As a result of colliding with the at least one blade 7 of the rotor 3 in a rotating state, the velocity of the source jet 5 is changed, as will be described in further detail hereinafter. The magnitude and/or the direction of the velocity of the source jet 5 is changed, that is, the rotor provides an accelerated jet of gas 12 having a final velocity vector v_f which is different to the initial velocity vector v_i .

The system 1 comprises a target holder 13. The target holder is configured to support a target 14. The target 14 may be a substrate comprising one or more material layers.

The positioning device 4 is configured to control relative position and/or orientation of the target holder 13 and the direction of motion of the accelerated gas 12. Where “relative position and/or orientation” is referred to, it will be understood that this may refer to a distance between direction of propagation of the accelerated gas 12 and/or an orientation of the target holder 13 with respect to direction of propagation of the accelerated gas 12. Therefore a positioning device may be configured to control 1, 2, or 3 translational degrees of freedom and/or 1, 2, or 3 rotational degrees of freedom. Although Figure 3 illustrates one positioning device 4, embodiments of the present invention may provide more than one positioning device, that is, the system may comprise at least one positioning device. For example, a first positioning device may be configured to control a position and/or orientation of the target holder and a second positioning device may be configured to control a position and/or orientation of the gas source. Additionally or alternatively a third positioning device may be configured to control a position and/or orientation of the rotor. The system may comprise one or more controllers configured to control one or more of the at least one positioning devices.

In the embodiment illustrated in Figure 3, the positioning device 4 is a platform 15 which supports the target holder 13 and is configured to control the orientation of the target holder 13 with respect to the direction of the accelerated gas 13. For example, the platform 15 may be configured to rotate the target holder 13 with respect to the direction of the accelerated gas 12 about one or more axes. The platform 15 may be configured to change the position and/or orientation of the target 13 with respect to the direction of motion of the accelerated gas jet 12. In some embodiments the target holder 13 and the platform 15 are integral, that is, the platform 15 is the target holder 13.

The positioning device 4 can allow the system to be configured such that the accelerated jet of gas 12 is incident on a target 13 at a grazing angle, that is, substantially parallel to the plane of the target 13 which may be a substrate, for example a planar substrate. This can allow efficient transfer of in-plane momentum to atoms comprising the substrate which can allow atoms to be moved within the

substrate, for example in an annealing process. This can help diffusion reactions on the surface of the substrate.

The positioning device 4 can allow the system to be configured such that the accelerated jet of gas 12 is incident on a target 13 at a normal angle, that is, substantially perpendicular to the plane of the target 13 which may be a substrate, for example a planar substrate. This can allow efficient transfer of out-of-plane momentum to atoms comprising the substrate which can allow efficiency of reactions within the substrate to be improved. Such reactions can include, for example, an oxidation reaction, a nitridation reaction, a hydrogenation reaction, a fluoridation reaction. Such reactions can include a reaction configured to move atoms deeper within the film surface to enhance a diffusion inside the film.

The acceleration of the source jet of gas can be analysed using collision and conservation laws. In use, the collisions may be partially inelastic depending on for example the choice of gas, the blade material.

Collisions and conservation laws

For a system consisting of two masses, a small mass m traveling initially at speed v and a large mass M traveling a speed V , then the conservation laws relate the initial speeds with the final speeds v' and V' as follows (assuming fully elastic collisions):

$$mv + MV = mv' + MV' \quad (1)$$

And the kinetic energy E_{kin} is given by

$$E_{kin} = \frac{1}{2}mv^2 + \frac{1}{2}MV^2 = \frac{1}{2}mv'^2 + \frac{1}{2}MV'^2 \quad (2)$$

Since $m \ll M$, the resulting absolute speed of m after the collision is $v' = 2V$ and the resulting kinetic energy for m after the collision is

$$E_{kin} = \frac{1}{2}mv'^2 = \frac{1}{2}m(2V)^2 = 2mV^2 \quad (3)$$

Then using the relation between the temperature and the kinetic energy of gas molecules at their average speed, an equivalent temperature T can be defined

$$\frac{1}{2}mv'^2 = \frac{3}{2}k_bT \quad (4)$$

Therefore, giving molecules a greater speed is equivalent to giving them a higher temperature.

The interaction between gas molecules and the rotor blades is now evaluated.

Referring to Figure 4, if the rotor is configured to rotate at an angular velocity ω about the axis of rotation 10, then the linear velocity V_p of a point P1 located on a blade 7 at a distance R from the axis of rotation 10 of the rotor 3 is given by

$$V_p = R\omega \quad (5)$$

- 5 Combining equations (5) and (4) provides the kinetic energy of a gas molecule 20 impinging on a blade 7 at point P:

$$E_{kin} = \frac{1}{2}mv'^2 = 2mR^2\omega^2$$

Thus, higher angular velocity of the rotor 3 when a gas molecule 20 impinges on a blade 7 leads to greater amounts of kinetic energy being transferred to the gas molecule 20 as a result of the collision.

- 10 Referring to Figure 5, a logarithmic plot of the kinetic energy of various gaseous species as a function of the rotation speed (rotations per minute) of the rotor is show. The energies are calculated for a collision point P1 located at $R = 6\text{cm}$ from the axis of rotation of the rotor.

It is noted that room temperature corresponds to a kinetic energy of approximately 25 meV, and a temperature of 1000K, being approximately the highest temperature used in growth, etching, treatment, annealing of thin films and/or substrates, corresponds to a kinetic energy of 100 meV, and

- 15 such temperatures are considered to be within reach of systems according to the present invention. Under these assumptions even for hydrogen, kinetic energies in excess of 1eV are possible. For argon – the most commonly used sputter gas – these conditions suggest that energies in excess of 1 eV could be possible. For the gas with the highest mass plotted in Figure 5, xenon, kinetic energies in excess of
- 20 10 eV could be possible.

Since the linear speed of a point on a rotating disk is proportional to the distance R of the point from the axis of rotation, the resulting kinetic energy of the gas molecule 20 will vary as the square of the distance R . This is illustrated in Figure 6, for which the angular speed of the rotor is 500,000 RPM, and it is assumed that the gas molecule impacts the blade at point P1 .

- 25 Referring to Figure 7, the linear velocity of the rotor (approximately twice this velocity is transferred to the molecules) is shown as a function of the radius of the rotor and angular velocity of the rotor. This velocity is compared with average value of a Maxwell-Boltzmann distribution for O_2 at 300K (around 480 m/s). Referring to Figure 8, if a blade has a dimension of dR in the radial direction as measured from the surface of the rotor cylinder (that is, perpendicular to the axis of rotation of the rotor) and the rotor cylinder has a radius of R , then the dimension of the blade in the radial direction
- 30 as measured from the axis of rotation will vary R and $R+dR$. The resulting range of speeds of the points

on the blade at which gas molecules impinge for $R = 3$ cm and $dR = 1$ mm is shown in Figure 7 as dV , which varies between 3141m/s and 3246 m/s.

The attainable blade linear velocity for a system 1 is limited by the material of which the blade 7 is made. The maximum attainable linear blade velocity v_{max} is given by

$$v_{MAX} = \sqrt{\frac{8\sigma_0}{(\nu + 3)\rho}}$$

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where ρ is the density of the blade material, σ_0 is the yield strength of the blade material, and ν is the Poisson modulus of the material.

The blade 7 may comprise, for example, titanium or a titanium alloy, stainless steel, aluminium alloy, carbon fiber, polymer, silicon.

- 10 The rotor may be a magnetically levitated rotor, that is, a rotor which levitates inside a bearing body. This can provide a reduced friction system which can allow higher rotational speeds. One such system is available from Celeroton AG (Switzerland). The company Celeroton also manufactures the electronics controller systems which may be used for driving a magnetic bearing motors. One such system is for instance the controller CC-AMB-1500 that can be used to operate the magnetic bearing
- 15 motor CM-AMB-400, which can be operated at 400,000 RPM.

Embodiments of the present invention can be used in thin film deposition systems, thin film etching systems, thin film cleaning systems. In some embodiments the system 1 may be contained inside or attached to a vacuum (or near ambient pressure) system. The accelerated gas jets can be directed at the substrate, a growing film, a target, or incorporated with a deposition, cleaning or etching

20 processes.

Referring to Figure 9, in some embodiments the system 1 comprises a first chopper 40 and/or a second chopper 41. The first chopper 40 is located between the gas source 2 and the rotor 3 in the propagation path of the source gas 5. The second chopper is located between the rotor 3 and the target holder 13 in the propagation path of the accelerated gas 12.

- 25 The first and second choppers 40, 41 may comprise one or more disks configured to rotate about an axis substantially parallel to a direction of propagation of a gas jet which is incident on the chopper. The one or more disks comprise one or more cut-out segments which can allow a gas to pass through the disk. By controlling the size and location of the cut-out segments and the rotation speed of the disks, this can allow a specific range of velocities to be selected from a gas jet incident on the disk. The
- 30 first and second choppers 40, 41 may comprise a linearly translatable sheet having one or more cut-out segments, configured to oscillate (that is, move back and forth) in a direction substantially perpendicular to a direction of propagation of a gas jet which is incident on the chopper.

The first chopper 40 is configured to select a specific range of velocities of the source gas 5 provided by the gas source 2. The second chopper 41 is configured to select a specific range of velocities of the accelerated gas provided by the rotor 3.

The system 1 may comprise a rotor controller configured to control the angular velocity of the rotor 3. By controlling the angular velocity of the rotor 3, the energy of the accelerated gas in the jet 12 can be controlled. It is noted that that most defect energy levels in thin films are of the order of eV, and so the ability to tune the energy of the accelerated gas easily and reproducibly from 25 meV to a few eV is advantageous. In some embodiments the rotation speed of the rotor 3 may be unchanged during a process. In some embodiments the rotation speed may be changed or alternated between different values during a process, in dependence upon the required energy for the process. The required energy may be chosen in order to obtain good thin film quality, annealing, cleaning, or etching.

The system 1 may comprise a gas supply valve configured to control an amount of source gas 5 provided by the gas source 2. By controlling the amount of source gas 5 that is capable of interacting with the at least one blade 7, the amount of accelerated gas 12 can be tuned from a low density flux to a high density flux. The source gas pressures used can be varied widely from very low (ultrahigh vacuum conditions) to very high (a few atmospheres) and may be determined in dependence upon a system in which the system 1 is operating. For example, if several pumps are to be used as in a differential pumping configuration then it would become possible to construct a high pressure gas source 2.

In some embodiments, more than one gas species may be provided. For example, the source gas 5 may comprise a mixture of species of gas. The gas source 2 may comprise a plurality of gas sources, each configured to provide a different species of gas. The different species of gas may be provided simultaneously or sequentially to the rotor 3. For example, oxygen may be provided as a source gas during a first stage of growth of an oxide film, and hydrogen could be provided during a second stage of growth in order to passivate potential electrical defects arising in the film. The rotation speed of the rotor 3 may be varied for each species of gas. The pressure of each species of gas at the gas source 2 may be varied. This can allow to provide a different kinetic energy for each gas species.

Each gas source may be configured to provide a source jet of gas which is laminar. Each gas source may additionally or alternatively be configured to provide a source jet of gas which is turbulent. This can additionally or alternatively allow to vary the type of flow regime for each gas species and/or for a particular gas species at different points in time. For example, the type of flow regime may be laminar for a first gas species and turbulent for a second gas species. The type of flow regime may be laminar for a first gas during a first time interval and turbulent for the first gas during a second time interval.

The shape of the blade 7 may be rectangular in cross-section, as in Figures 3 and 4, that is, a surface 22 of the blade 7 with which the gas molecules 20 make contact is flat. In some embodiments, the surface 22 is not flat. For example, the surface 22 may be convex or concave. This can allow to produce a more converging or more diverging jet of accelerated gas. A more converging jet may be desirable in implementations in which the energy supply to the target is desired to be targeted. A more diverging jet may be desirable in implementations in which the energy supply to the target is desired to be homogeneous over a large area, for example over the whole surface of a substrate or target.

In some embodiments the rotor 3 comprises at least two blades 7 and each of the at least two blades 7 has a different blade surface 22, for example flat, convex, concave. This can allow to provide sequentially a different distribution of accelerated gas, for example if a wide jet of accelerated gas is desired. In some embodiments, for example if a large area wafer is desired to be processed, a system 1 comprising a plurality of gas sources may be provided, each gas source having a different orientation with respect to the rotor 3, and this can allow accelerated gas jets to be produced covering a wide target area. In some embodiments, a plurality of systems 1 may be provided in parallel and this can allow a plurality of accelerated gas jets to be provided.

In embodiments of the present invention the accelerated jet of gas is a continuous flux of accelerated gas. This accelerated jet of gas may be supplied during the growth of a thin film. It is an advantage of embodiments of the present invention that the accelerated gas, for instance argon, gives enough energy to the growing surface to help the crystallization of the thin film. It is thereby an advantage of embodiments of the present invention that the entirety of a target, or substrate, is not heated, as is the case in prior art systems, but that only the top surface atoms of the target or substrate is heated. In embodiments of the present invention, the depth to which the surface of the substrate is heated can for example be regulated by controlling the speed and temperature of the accelerated jet of gas. The depth may be several nanometers deep (e.g. 0.1 nm deep, or even 1 nm deep, or even 10 or 100 or 1000 nm deep) when channeling effects are considered. It is an advantage of embodiments of the present invention that the thermal energy of the gaseous species is given to a few surface atoms so that they can form a crystalline nucleus or a growth front can be continued.

In alternative embodiments of the present invention a pulsed flux of accelerated gas 12 may be used. This can be achieved by varying the rotation speed of the rotor 3 and/or by controlling a valve (not shown) configured to control the amount of source gas 5 which is provided from the gas source 2. In that case first all the atoms preferably forming a unit cell of the required compound, can be deposited on the substrate for instance and then the temperature is increased under the bombardment of the accelerated gas. This process can be advantageous compared to the regular thin film deposition

processes where partial unit cells are continuously formed at high temperature but that is frequently and inherently not as stable as the full unit cells, in particular for complex unit cells. For instance for some compounds a high temperature step is required to form a crystal but at that temperature part of the material will evaporate. This is for example the case for InGaZnO compounds, the invention not being limited thereto. In embodiments of the present invention such compounds are for instance deposited in a structure of 3 monolayers with the most stable layer as last (final deposited) layer. A heating step is provided before, after, or simultaneously with this deposition step. The heating step allows the structure to be heated and to react to form a crystal. It is an advantage of this method according to the present invention that less material re-evaporates than in the standard process where all three elements are evaporated simultaneously.

In embodiments of the present invention a flux of accelerated gas is applied for supporting the growth of thin films. In further embodiments of the invention, the above-mentioned two methods may be used in combination with a varying substrate temperature. The substrate temperature can be cooled or heated to adjust the thermal budget to which the surface is exposed. This can be optimized for instance to prevent the appearance of defects in the grown material.

Heating of the surface of a substrate or target using an accelerated jet of gas in accordance with embodiments of the present invention may also be applied to obtain a thin film with gradient composition and/or strain. As opposed to prior art methods where a high temperature substrate is used, this can be done by adjusting the composition and/or the temperature of the accelerated jet of gas while growing the thin film. In embodiments of the present invention the gas elements can be changed during the growth of the thin film either in a pulsed fashion, a gradient fashion, in a bilayer fashion or in a multilayer fashion. Controlling the depth of the heating profile can be done by selection of the elements of the jet of accelerated gas, for example by providing a plurality of gas sources and gas source valves and by controlling the amount of each type of source gas which is provided from each gas source using the gas source valves. The gas source may for instance be adapted for evaporating elements which have a predetermined atomic radius. The depth can be limited to only the surface atoms by using heavy elements. With very light elements it is possible to go subsurface partially due to channeling processes. Heavy and light elements can alternate both with different duration and pressure. Heating of the surface of a substrate or target using an accelerated jet of gas in accordance with embodiments of the present invention may also be applied to flatten the surface of the substrate. This may be done by heating the surface at a temperature which is high enough to increase lateral diffusion substantially up to melting and flatten the surface of the substrate or of a deposited film or structure.

In embodiments of the present invention a first accelerated jet of gas can be provided wherein the accelerated jet of gas at least comprises inert elements and a second accelerated jet of gas can be provided wherein the second accelerated jet of gas comprises reactive elements. Reactive elements which can be used are for example hydrogen, oxygen, nitrogen. This will not only lead to heating the surface but will advantageously also lead to enhanced reduction, oxidation and/or nitridation and other reactions. This process also may include the use of the reactive gases applied "cold", i.e. they are not heated or cooled intentionally, in combination with the hot inert (e.g. noble) gases.

In embodiments of the present invention the accelerated jet of gas may be used for a solid phase epitaxy process whereby first all the required elements are deposited on the substrate at low temperature and in a nearly amorphous state, and then preferably an annealing treatment is performed whereby the film is crystallized.

In embodiments of the present invention a combination of high energy (hot) gases and low energy (cold) gases can be provided using the system 1. These gases can be the same species or any combination of noble and reactive species. The use of cold gases for instance in a pulsed combination with the hot gases offers additional process tuning possibilities. This can be realised by changing the speed of the rotors between a relatively high energy (relatively fast rotation speed) and a relatively low energy (relatively slow rotation speed) state. This can alternatively be realised by changing the species of the source gas, for example alternating a heavy molecule with a lighter molecule.

Embodiments of the present invention can allow a patterned thin film layer to be grown with use of a photoresist. This is typically not possible at high temperatures as the photoresist can react and decompose at these temperatures. The present invention allows a substrate surface to be heated such that an overlying photoresist may be partially affected by high energy gases at its surface but will not entirely decompose or be removed. Embodiments of the present invention allow to direct the accelerated gas jet to open regions (that is, regions wherein the surface of the substrate is exposed by the photoresist mask) and to perform targeted patterned thin film layer growth.

Accelerated jets of gas in accordance with embodiments of the present invention may also be used in etching processes. This can be done in a global manner but it can also be done using the standard lithography procedures whereby masks and resists - or solid layers - are used to define areas wherein the material can be removed. For the etching process, the mechanism that is preferably used in this invention is the re-evaporation of material when treated to a high temperature step. For simple metals and elements the re-evaporation rates are well defined as a function of temperature and pressure. In embodiments of the present invention a compound gas mixture may be used for a reactive etching process. Such a gas may for example comprise the well known reactive ion etch gases fluorides, chlorides and/or borides. The reactive gasses may be supplied at high temperature or at low

temperature. When supplied at low temperature the substrate may for example be pre-heated using an accelerated jet of gas. It is an advantage of embodiments of the present invention that heating of the surface of the substrate 140 using an accelerated jet of gas ($> 1500^{\circ}\text{C}$) allows to develop good etching processes without the need of adding ionic and radical components to the gas mixtures.

5 In embodiments of the present invention, systems 1 can be implemented in any existing deposition process system such that the relative orientation of the accelerated gas jet and a target holder is controlled. The gas source 2 can be positioned at a range of angles compared to the plane of the rotating blade and gas flow from the gas source 2 can be controlled in a standard way using pressure sensors, flow meters, barotrons, on/off valves or shutters as is custom in state of the art systems. The
10 speed of rotation of the rotor 3 can be adapted at will continuously or in a single ramp, or multiple ramps, periodic oscillation or any irregular pattern optimised for a given process.

In embodiments of the present invention, a plurality of systems 1 can be provided, each providing a particular gas, the plurality of systems 1 having a particular rotor configuration, e.g. each system having a predetermined rotation speed or a rotor with different radius or with different blade
15 configuration, having particular gas inlets and having a specific overall configuration. This can allow the deposition / etching process to be homogenized for instance or to allow a continuous mixing process of the different gases.

In embodiments of the present invention, the rotor rotation speed and configuration can be used to break up / crack chemical molecules as in the case of metal-organic precursors. This can be beneficial
20 as it can be the case that chemical precursors to be provided to a substrate are required to be broken up by heat provided by the substrate, which is often a serious limitation. Chemical precursors are the main source elements of processes such as atomic layer deposition (ALD); chemical vapor deposition (CVD) and all their variants and all share the challenge that the precursors need substrate heat to decompose and lead to film growth. For instance TEOS (a silicon precursor) needs temperature around
25 800°C in order to break up and be used as a source of silicon. By breaking TEOS using the systems 1 according to embodiments of the present invention this can be a great benefit for deposition processes since a heated substrate is no longer needed to break TEOS. This can be implemented as a stand-alone system 1 or by using a plurality of systems 1. In these implementations, the TEOS molecules receiving high energy gas molecules will decompose accordingly and leave Si atoms on the
30 surface.

Similarly, embodiments of the present invention allow the standard gas molecules such as water, oxygen, nitrogen, hydrogen, to be broken up into their atomic - and much more reactive - constituent parts. By varying the rotation speed of the rotor 3, the fraction of atomic species can be controlled precisely and reproducibly.

In embodiments of the present invention, the system may comprise one or more pairs of metallic plates, each pair of metallic plates having a voltage applied between plates in the pair. The plate pairs are located between the rotor and the target holder, along the path of the accelerated gas jet, and can allow to attract and remove charged species from the beam which may be generated through collisions with the rotor and/or break-up processes.

Embodiments of the present invention allow to alternate the deposition of chemical precursors - in their original or in their broken down form - with gas molecules, for example as in an atomic layer deposition process. This can be implemented by using a system 1 having a plurality of gas sources, each configured to provide a different gas species, each gas source also having a respective control valve. This can allow precursors to be first deposited on the surface and subsequently broken down using reactive species such as water. This can alternatively be implemented with an additional heating step using a short pulse of high energetic species to initiate or continue film growth and/or crystallisation.

In embodiments of the present invention, the system 1 may comprise a second rotor configured to receive an accelerated gas jet from the first rotor 2 and the second rotor can function as a filter for the accelerated gas provided by the first rotor. This can allow to filter out part of the velocity distribution of the accelerated gas provided by the first rotor and create a narrower velocity distribution. Alternatively, if different species are comprised in the accelerated jet of gas provided by the first rotor, for instance due to molecules being broken down into constituent parts, which cost energy and thus change the speed of the molecules, then the velocity distribution can also change. For example, the second rotor may function as a chopper (that is, be capable of blocking some velocities and allowing other velocities to pass through) which is also capable of providing additional momentum to the molecules, by changing the speed and/or direction. The first rotor and the second rotor can be positioned in series wherein the first rotor leads to collisions and creates a first accelerated beam, and the second rotor provides velocity selection and/or filtering. In some embodiments the second rotor may allow to deviate the accelerated jet of gas provided from the first rotor beam into another direction or change the angle of distribution of the accelerated jet of gas.

In embodiments of the present invention, the rotor blade 7 may be heated by a rotor heater element (not shown), for instance through the pressure of heating lamp or laser beam that will heat a surface of the blade. This can help in the break-down of molecules and/or can allow a temperature or speed of the molecules to be increased further.

In some embodiments, the temperature of the gas in the gas source and be heated or cooled to change the average speed or speed distribution of the gas molecules

In some embodiments, in dependence on the gas molecules involved and any material comprising the blade or coating on the blade, the collisions of the gas molecules with the blade may become more or less elastic. For example, a hard coating can lead to collisions which are more elastic, which can allow to provide a sharp (relatively narrow) velocity distribution. A softer coating can lead to collisions which are less elastic, which can allow to provide a broader velocity distribution.

In embodiments of the present invention the system 1 can be installed in or along with any thin film deposition process system, for example a system that performs any of sputtering, laser ablation, molecular beam epitaxy, chemical beam epitaxy, chemical vapour deposition, physical vapour deposition, metals-organic vapour deposition, atomic layer deposition. When used together with those systems, an accelerated gas jet can be directed at a substrate and can improve the crystallization processes involved. This can be done in a continuous mode or in a pulsed mode whereby at least one first layer is deposited on the substrate in a deposition step and is then heated using the accelerated gas jet. In some embodiments the substrate may be heated using the accelerated gas jet before and/or during the deposition step. In some embodiments a pump for differential pumping may be provided around the system 1.

In embodiments of the present invention, the accelerated gas jet could be directed towards a target material source and be used in a sputtering / laser ablation configuration. Sputtering processes can be performed in this manner without the need of ionic species.

In thin film growth processes, typically fluxes of elements are provided to a substrate at high temperature. For example, for the growth of magnesium oxide on silicon, a growth temperature of 200 to 800° has been used. This was done using a variety of deposition methods including molecular beam epitaxy. For the latter process, the flux of magnesium metal atoms is aimed at the substrate in the presence of an oxygen background pressure.

In molecular beam epitaxy, the oxygen pressure is typically not higher than approximately 10⁻⁵ Torr.

According to embodiments of the present invention, the substrate temperature remains at room temperature, while the accelerated gas jet is provided to the substrate surface to heat it up. The accelerated gas jet may comprise argon gas. The flux and the kinetic energy of the argon atoms determines how "hot" the substrate surface becomes. In some embodiments the accelerated gas jet and the evaporant fluxes (the material leaving the Mg source and impinging on the surface of the substrate) are provided simultaneously to the substrate. This can allow the surface layer temperature to remain constant during a growth process. In some embodiments the timing of the fluxes is varied such that the deposition and the heating occur sequentially instead of simultaneously. The evaporant flux source may be for example a heated effusion cell or an electron beam gun in MBE applications, a gas line in CVD applications, in other applications may be a liquid solutions.

Molecular beam epitaxy is a relatively low pressure deposition technique. It can be difficult to obtain a high substrate surface layer temperature while maintaining a good vacuum condition. Embodiments of the present invention allow to alternate a low pressure deposition step with a higher pressure / flux annealing step. The substrate may also be preheated partially, for example to 300°C, so that only a smaller temperature interval needs to be supplied by the accelerated gas jet. An additional variable is to change the kinetic energy and the momentum of the accelerated gas jet as described herein.

In some molecular beam epitaxy processes, surface preparation steps are preferably used whereby heating of the substrate is required for instance to desorb impurities or to induce a specific surface reconstruction. This preparation can also fully be prepared with the accelerated gas jet either as the only heating source or in conjunction with an intermediate substrate heating level. An illustrative example is the cleaning of HF prepared silicon substrates. These surfaces are hydrogen terminated upon insertion into the vacuum system. Upon heating the substrate to about 500 °C, preferably above 150°C, the hydrogen species desorb as can be easily determined using a quadrupole mass spectrometer. The same phenomenon can be easily observed by supplying an accelerated gas jet to the substrate. In some embodiments, the accelerated gas jet could first be used to clean a surface by using etching gasses or simply by heating the surface so that contaminants evaporate or by bombarding with high energy and sputtering away surface contamination.

In embodiments of the present invention accelerated gas jets may be used in systems wherein high pressure processes are already present. This includes processes such as ALD, sputtering, CVD, PCVD, MOCVD etc. The substrate can be preheated to a certain value either using the standard substrate heating mechanisms, using the accelerated gas jet or using a combination of both. It is an advantage of embodiments of the present invention that using the accelerated jet of gas the surface layer can be heated to a higher temperature as this may provide additional possibilities for cleaning and growth. A few interesting examples are those of the growth of SiC and of diamond. Both materials require a very high temperature which is not easily accessible for the growth on silicon. It is therefore an advantage of embodiments of the present invention that very high substrate surface layer temperatures can be obtained.

In embodiments of the present invention accelerated gas jets may be used in annealing processes. In these embodiments a heating step is applied during a predetermined time. The process may be complemented by adding additional gaseous reactive elements such as to induce an oxidation anneal or a reduction anneal, if required. An example on standard treatment in the literature is a forming gas anneal using for instance a mixture of Argon and Hydrogen at a substrate temperature of 350 - 450 degrees Celsius. A similar process can be done using the accelerated jet of gas.

In embodiments of the present invention accelerated gas jets may be used in etching processes. This can be done in a global manner but it can also be done using the standard lithography procedures whereby masks and resists - or solid layers - are used to define areas wherein the material can be removed. For the etching process, the mechanism that is preferably used in embodiments of this invention is the re-evaporation of material when treated to a high temperature step. For simple metals and elements the re-evaporation rates are well defined as a function of temperature and pressure. In embodiments of the present invention a compound gas mixture may be used for a reactive etching process. Such a gas may for example comprise fluorides and/or borides. The reactive gasses may be supplied at high temperature or at low temperature. When supplied at low temperature the substrate may for example be pre-heated using a hot jet of gas. It is an advantage of embodiments of the present invention that use of accelerated gas jets allows to develop good etching processes without the need of adding ionic and radical components to the gas mixtures.

In embodiments of the present invention accelerated gas jets may be used in forming evaporation sources by etching away material from a material source. Like in ALD and CVD processes where the precursor vapor are carried with the help of carrier gas at a relatively high pressure, the same can be done here. One advantage of this method is that also the pure elements can be evaporated even those that require a very high evaporation temperature. It is moreover an advantage of embodiments of the present invention that they can be used both for elemental materials as for different compounds. In embodiments of the present invention the accelerated jet of gas is supplied to a crucible wall whereby the crucible material is made of the material one wants to evaporate. It is an advantage of embodiments of the present invention that thereby a new elemental deposition source is created. The elemental deposition source comprising a heating device 100 according to embodiments of the present invention and a crucible wall or target made of the element one wants to deposit. The crucible wall and the heating device are thereby positioned such that, when operational, the hot jet of gas of the heating device passes at the surface of the crucible wall thereby removing atoms from the crucible. Under the appropriate conditions of temperature, pressure and flow, a significant density of crucible atoms will evaporate and become part of the gas stream. This gas stream can then be driven over the surface of a substrate and lead to the deposition of the said element. This process will be particularly useful for metals which have a low vapor pressure such as for instance Hf (hafnium). These materials typically require temperatures in excess of 2200 °C for a flux to appear. It is an advantage that systems 1 can provide an accelerated jet of gas in accordance with embodiments of the present invention. In prior art systems these metals may be evaporated using electron beam guns or alternatively the metal is packed inside an organic compound in processes such as ALD and CVD but unfortunately these also may contain a lot of unnecessary carbon that preferably is removed subsequently.

In embodiments of the present invention accelerated gas jets may be used for surface cleaning wherein surface impurities on a substrate can be evaporated.

In embodiments of the present invention accelerated gas jets may be used for surface implantation, doping, and/or hardening. A desired species can be implanted at a subsurface level such as carbon
5 which could lead to hardening of the film or substrate. This can also be used to implant dopants. One of the typical difficulties with dopant implantation clustering which can occur when high dopant concentrations are reached. This can reduce the effective carrier concentration. A low temperature deposition / implantation process using systems according to embodiments of the present invention can allow the implantation / doping during the growth to be more effective and can allow dopant
10 atom clustering to be avoided.

In embodiments of the invention the accelerated gas jets are used for dopant activation anneals whereby dopants atoms are moved to their correct position into the lattice for instance of Si, Ge, GaAs and other materials.

In embodiments of the invention the accelerated gas jets are used for defect passivation anneals
15 whereby defect atoms are moved to their correct position into the lattice for instance of Si, Ge, GaAs and other materials. This can be performed using reactive gases such as hydrogen either "cold" or accelerated.

Embodiments of the present invention allow to provide an accelerated gas jet with the possibility to adjusting the composition and temperature of the accelerated gas. This can allow a film with gradient
20 composition or strain to be formed. This is not possible using standard methods whereby a high temperature substrate is used and diffusion processes can reduce the gradient structures.

Embodiments of the present invention can allow to grow thin films essentially on any substrate which can be paper, plastic, wood, tissue, without requiring heating of the substrate.

Embodiments of the present invention can be used in processes involving volatile components. Many
25 volatile materials (metals, oxides, hydrides, nitrides, arsenides, phosphides, etc) when heated up tend to decompose or evaporate. In some cases this can lead to evaporation or decomposition at a temperature which is less than a temperature at which the components would be capable of forming a good single crystal. For example, for the growth of GaN, in principle a high pressure of nitrogen is required unless a reactive nitrogen species is used. This is also the case for InGaZnO, wherein the
30 composing elements / oxides are volatile at temperatures which are less than a temperature at which a good crystal structure can be formed. This is also the case of InGaAs where the material decomposes at modest temperature / high pressure and thus requires the growth in the presence of a large As background pressure. These limitations can be addressed by using accelerated gas jets according to the present invention. For instance, in the case of oxides it is also possible to use atomic oxygen broken

up by the energetic collision between molecular oxygen and the blade, as described hereinbefore. In the case of arsenides and phosphides several precursors can be used for this purpose, for example arsine (AsH_3), tertiarybutylarsine (TBAs), phosphine (PH_3), tertiarybutylphosphine (TBP), etc. This general principle can be used for all thin films and compounds that can contain volatile / non-volatile compounds.

In embodiments of the present invention an accelerated gas jet can be used for enhanced surface diffusion up to surface melting and flattening. This process can also be enhanced by using hydrogen or other gases as an energetic (accelerated) gas source during pre-annealing, growth or post-annealing.

Embodiments of the present invention allow to control the stress related to lattice mismatch combined with the thermal mismatch. Use of accelerated gas jets according to embodiments of the present invention allow that the substrate does not need to be heated so much and the thermal stress induced by the difference in thermal expansion can be much better managed. This can allow to eliminate one of the main sources of defects in thin film processes.

Embodiments of the present invention can be used to control a thin film growth mode. Depending on the specifics of the film material and the underlying layers or substrate, the growth mode can be a two dimensional layer by layer growth (unit cell by unit cell) or a more three dimensional grain growth process. A higher temperature used during growth can lead to a rougher surface and grains that grow along preferential directions. Embodiments of the present invention allow to control the surface temperature using accelerated gas jets. This can allow the growth mode to be changed accordingly which can lead to flatter and higher quality thin films.

Embodiments of the present invention may also be applied for rapid thermal annealing (RTA) including rapid cooling. It is thereby an advantage of embodiments of the present invention that only the surface of the substrate is heated by an accelerated gas jet and that therefore the cooling rate is much faster than in the case the complete substrate would have been heated. This is particularly advantageous since in most RTA applications the limiting factor is the speed at which the substrate can cool down again. Since there is a very high substrate mass, the cooling rate is defined by that of the substrate mass when the complete substrate is heated.

Modifications

It will be understood that many modifications of embodiments of the present invention described herein are possible.

For example, referring to Figure 10, the positioning device 4 may comprise a platform 16 which supports the rotor 3 and the gas source 2 and is configured to control the relative position and/or orientation of the target holder 13 with respect to the direction of the accelerated gas 12. For

example, the platform 16 may be configured to rotate the rotor 3 and the gas source 2 with respect to the target holder 13. The platform 16 may be configured to translate the rotor 3 and gas source 2 with respect to the target holder 13. The platform 16 may be configured to rotate about one or more axes. The platform 16 may be configured to translate in one or more directions.

- 5 The platform 16 may be provided in two parts, that is, a first platform part configured to control the relative position and/or orientation of the gas source and the rotor, and a second part configured to control the relative position and/or orientation of the rotor and the target holder. This embodiment would allow to change the position and/or orientation of gas source relative to the rotor blade and would allow to keep the rotor position and/or orientation fixed towards the target holder even as the
- 10 speed of the accelerated gas changes.

In some embodiments, the positioning device 4 may comprise the platform 16 and the target holder 13 may be fixed, that is, incapable of being rotated or translated. In other embodiments the positioning device 4 may comprise the platform 16 and the platform 15, that is, both the target holder 13 and the rotor and gas source are capable of being rotated and/or translated. The system may

15 comprise a positioning controller configured to control the at least one positioning device.

The system may comprise one or more vacuum pumps configured to evacuate gas molecules. The system may be comprised in a vacuum chamber.

The gas source may comprise a temperature controller configured to control a temperature of the source gas provided by the gas source.

- 20 The system may comprise a rotor temperature controller configured to control a temperature of the rotor and/or the at least one blade.

Claims

1. A system (1) comprising:
a gas source (2), a rotor (3), at least one positioning device (4), a target holder (13);
wherein the gas source (2) is configured to provide a source jet of gas (5) towards the rotor
5 (3);
wherein the rotor (3) is configured to change the velocity of the source jet of gas (5) to
provide an accelerated jet of gas (12); and
wherein the at least one positioning device (4) is configured to control a relative position
and/or orientation of the accelerated jet of gas (12) from the rotor (3) and the target holder
10 (13).
2. A system (1) according to claim 1, further comprising a chopper (40) disposed between the
gas source (2) and the rotor (3).
3. A system (1) according to claim 1 or 2, further comprising a chopper (41) disposed between
the rotor (3) and the target holder (13).
- 15 4. A system (1) according to any preceding claim, wherein the gas source (2) is configured to
provide a source jet of gas (5) which is laminar.
5. A system (1) according to any preceding claim, wherein the gas source (2) is configured to
provide a source jet of gas (5) which is turbulent.
6. A system (1) according to any preceding claim, wherein the gas source (2) comprises a
20 temperature controller configured to control a temperature of the source gas (2).
7. A system (1) according to any preceding claim, further comprising a rotor temperature
controller configured to control a temperature of the rotor.
8. A system (1) according to any preceding claim, further comprising a rotor controller
configured to control rotation speed of the rotor.
- 25 9. A system (1) according to any preceding claim, further comprising a positioning controller
configured to control the positioning device.
10. A system (1) according to any preceding claim, wherein the source jet of gas comprises
reactive elements.
11. A system (1) according to any preceding claim, wherein the source jet of gas comprises inert
30 elements.
12. A system (1) according to any preceding claim, wherein the source jet of gas comprises
neutral elements.
13. A system (1) according to any preceding claim, wherein the target holder supports a target
and the positioning device is configured to direct the accelerated jet of gas towards a target.

14. A system (1) according to claim 13, wherein the target comprises a substrate.
15. A system (1) according to claim 14, wherein the substrate comprises a single material.
16. A system (1) according to claim 14, wherein the substrate comprises a base layer and at least one thin film layer on the base layer.
- 5 17. A system (1) according to any one of claims 13 to 16, wherein the target comprises a specified position on a substrate.
18. A system (1) according to any of the previous claims, wherein the system is adapted for rotating the target holder during the provision of the source jet of gas in order to improve or ensure homogeneity of the impingement of the accelerated gas jet on the target holder or
- 10 on a substrate positioned in the target holder.
19. A system (1) according to claim 18, wherein rotating of the target holder comprises providing a rotation with a rotation axis perpendicular to the substrate.
20. Use of a system (1) according to any preceding claim in an annealing process.
21. Use of a system (1) according to any of claims 1 to 19 in a thin film cleaning process.
- 15 22. Use of a system (1) according to any of claims 1 to 19 in a thin film deposition process.
23. A method of treating a substrate, comprising:
providing a system (1) according to any of claims 1 to 19;
providing the substrate in the target holder (4); and
directing the accelerated jet of gas (12) towards the substrate using the positioning device
- 20 (13).
24. A method according to claim 23, wherein the accelerated jet of gas (12) is directed towards a defect site on the substrate.
25. A method according to claim 23 which is an etching method.
26. A method according to claim 23 which is a substrate cleaning method.
- 25 27. A method according to claim 23, further comprising a deposition step for depositing sample material for a thin film on the substrate.
28. A method according to claim 27, further comprising providing a lithography mask on a surface of the substrate.
29. A method according to claim 28, wherein the lithography mask comprises photoresist.

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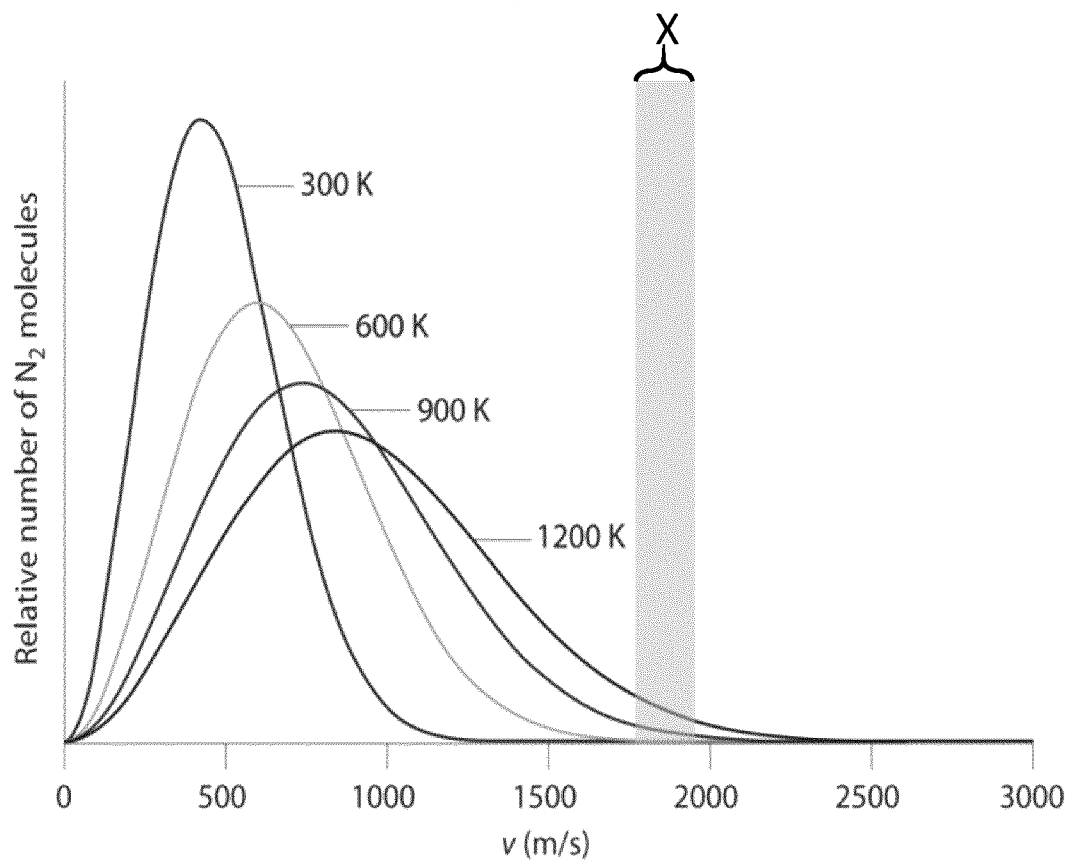


Fig. 1

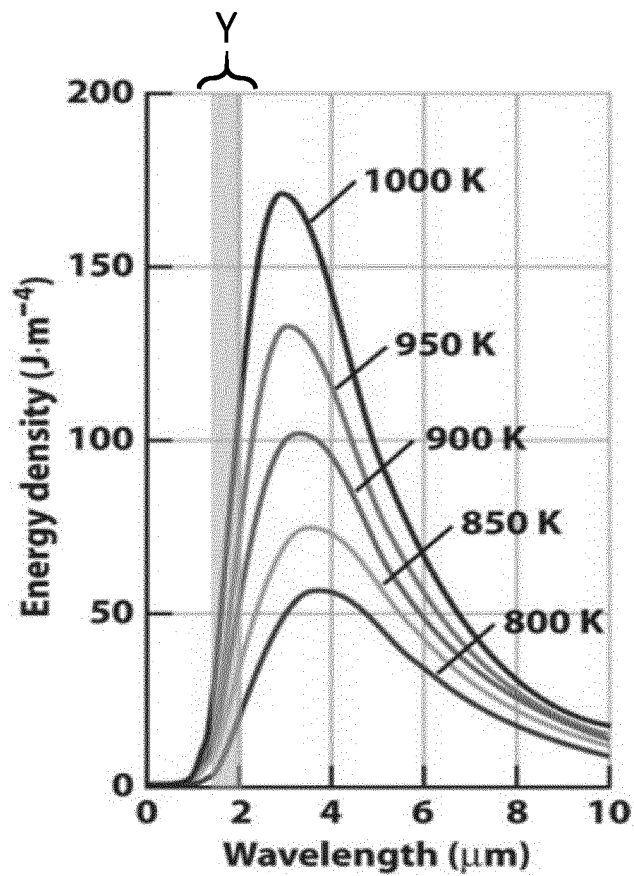


Fig. 2

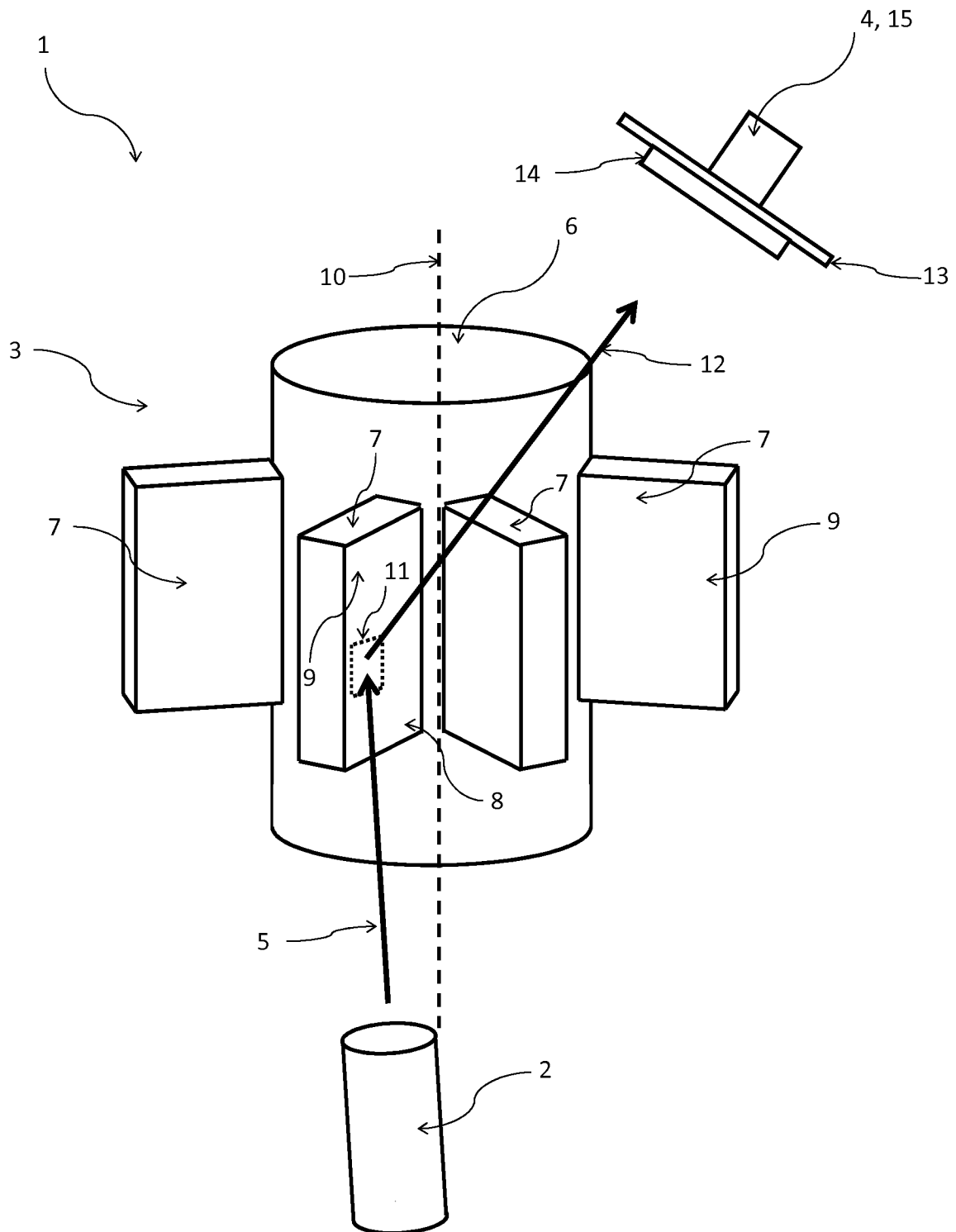


Fig. 3

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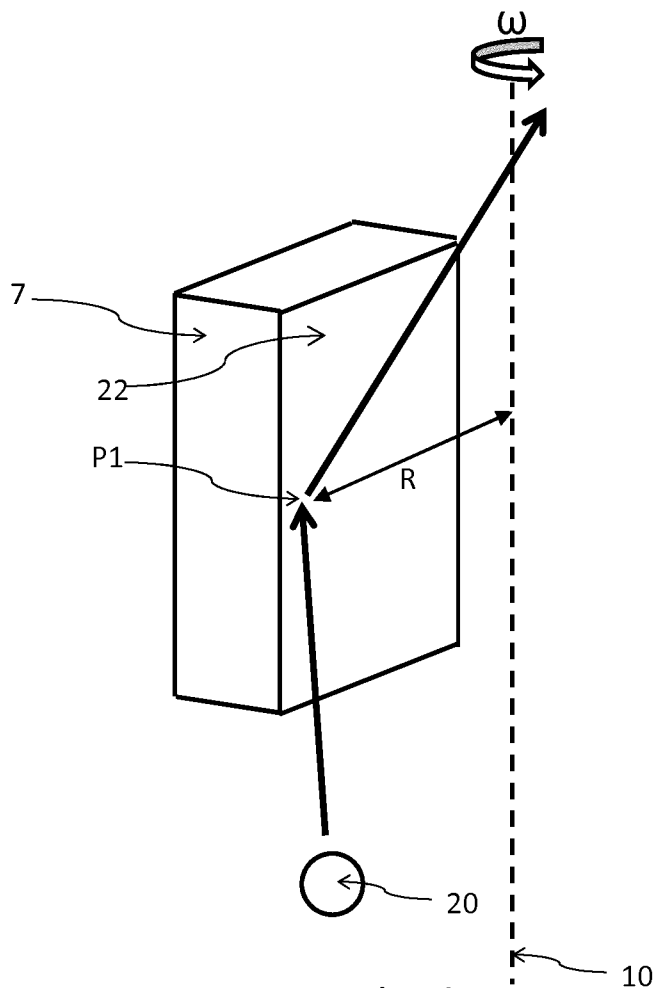


Fig. 4

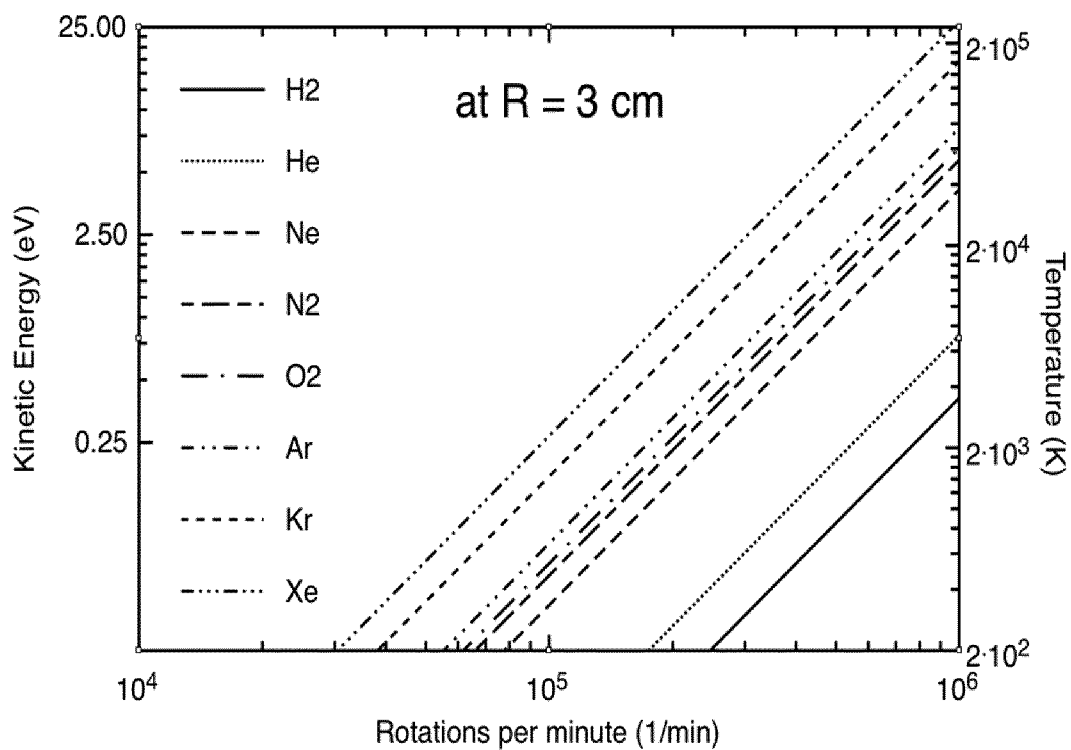


Fig. 5

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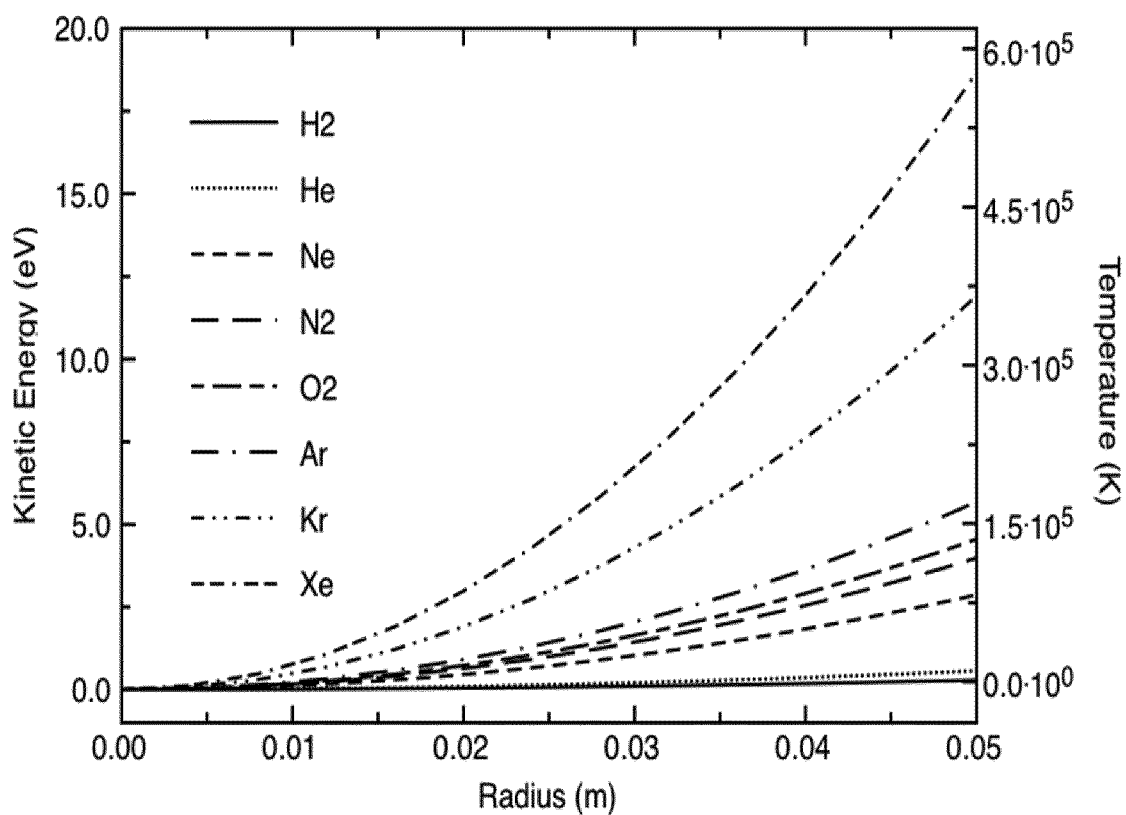


Fig. 6

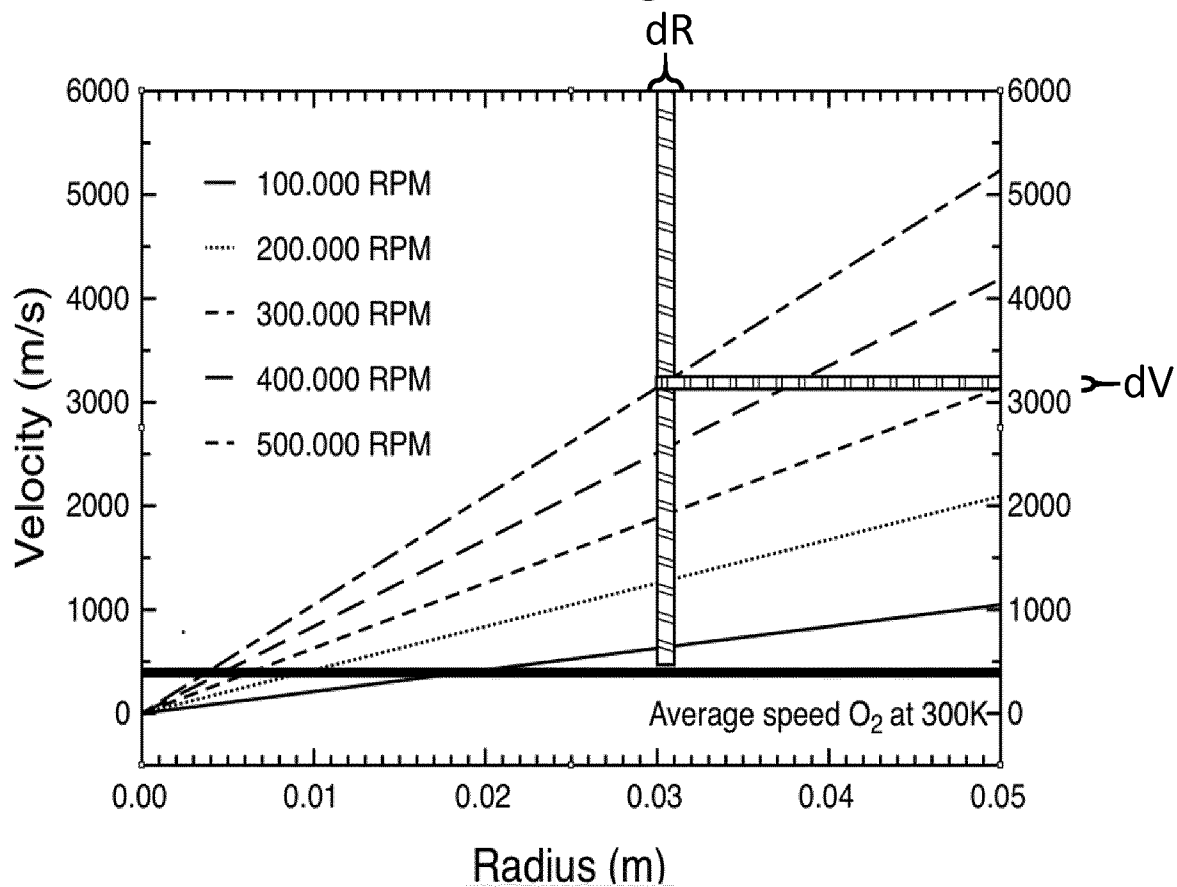


Fig. 7

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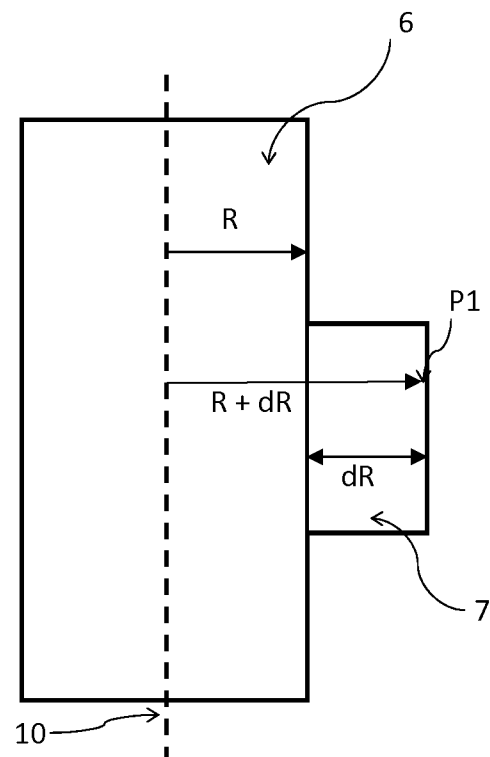


Fig. 8

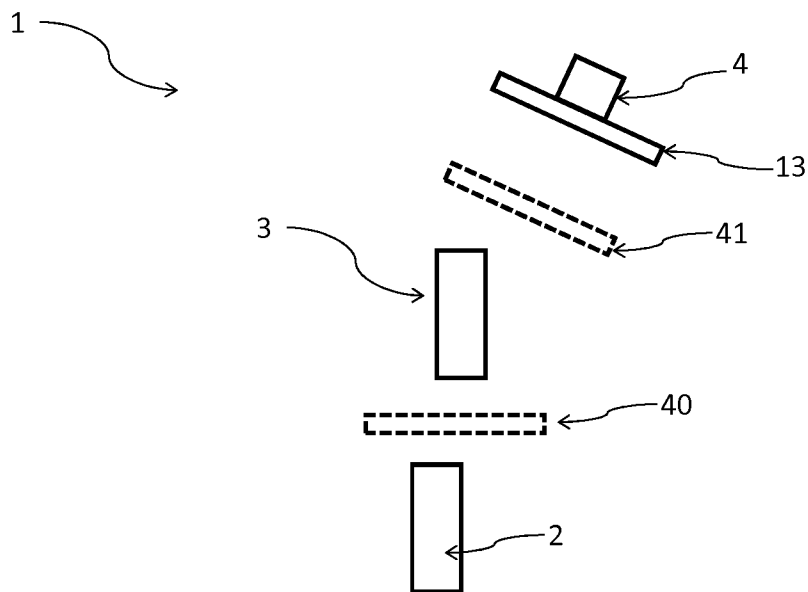


Fig. 9

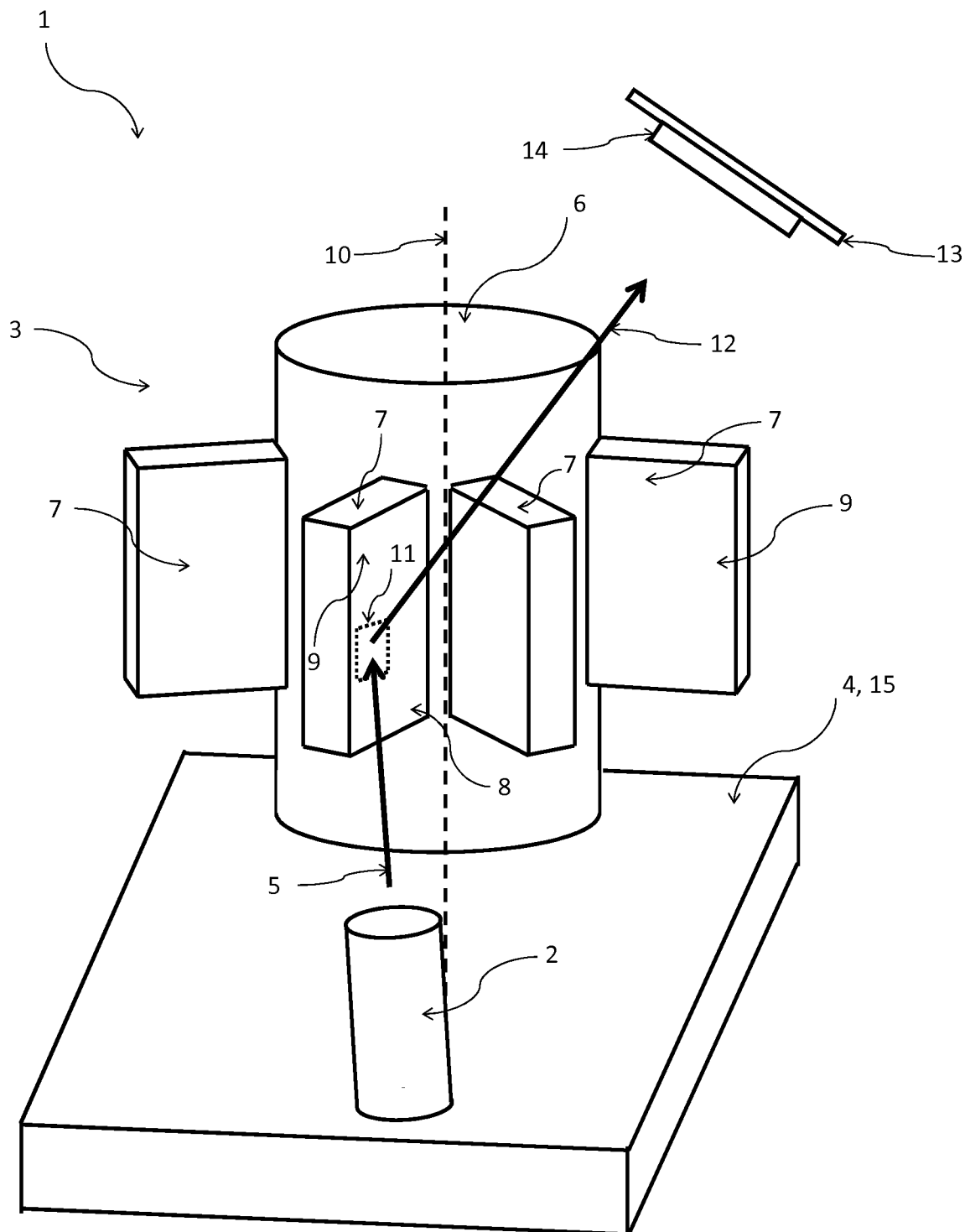


Fig. 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2018/073408

A. CLASSIFICATION OF SUBJECT MATTER

INV. C23C14/22 C30B25/14 C23C16/455 C23F4/00 H01J37/32
H01L21/00

ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

C23C C30B C23F H01J H01L C21D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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

EPO-Internal, WPI Data, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP H08 17747 A (TOKYO ELECTRON LTD) 19 January 1996 (1996-01-19)	1-4, 6-19, 21-29
A	the whole document	5,20
X	BE 890 394 A (ROECHLING BURBACH GMBH STAHL) 18 January 1982 (1982-01-18)	1,5, 11-15,20
A	the whole document	2-4, 6-10, 16-19, 21-29
A	US 5 076 877 A (UEDA TETSUYA [JP] ET AL) 31 December 1991 (1991-12-31) the whole document	1-19
	----- -/-	



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

26 November 2018

Date of mailing of the international search report

11/12/2018

Name and mailing address of the ISA/

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Authorized officer

Abrasonis, Gintautas

INTERNATIONAL SEARCH REPORT

International application No.
PCT/EP2018/073408

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

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

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

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

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☒ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2018/073408

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 3 012 921 A (VAUGHAN ROBERT T) 12 December 1961 (1961-12-12) the whole document -----	1-29
A	JP H04 16233 A (HITACHI LTD) 21 January 1992 (1992-01-21) the whole document -----	1-29
A	JP S62 51211 A (DAINAMITSUKU INTERNATL KK) 5 March 1987 (1987-03-05) the whole document -----	1-29
A	HALPERN B L ET AL: "Gas jet deposition of thin films", APPLIED SURFACE SCIENCE, ELSEVIER, AMSTERDAM, NL, vol. 48-49, 1 January 1991 (1991-01-01), pages 19-26, XP027176976, ISSN: 0169-4332 [retrieved on 1991-01-01] the whole document -----	1-29
A	US 5 725 672 A (SCHMITT JEROME J [US] ET AL) 10 March 1998 (1998-03-10) the whole document -----	1-29
A	US 5 164 040 A (ERES DIULA [US] ET AL) 17 November 1992 (1992-11-17) the whole document -----	1-29
A	WO 2016/016465 A1 (UNIV LEUVEN KATH [BE]) 4 February 2016 (2016-02-04) the whole document -----	1-29

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2018/073408

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
JP H0817747	A	19-01-1996	NONE
BE 890394	A	18-01-1982	AT 374830 B 12-06-1984 BE 890394 A 18-01-1982 CH 647260 A5 15-01-1985 DE 3035032 C1 26-08-1982 ES 8303536 A1 16-02-1983 FR 2490243 A1 19-03-1982 GB 2083898 A 31-03-1982 IT 1224084 B 26-09-1990 JP S5785934 A 28-05-1982 JP S6410579 B2 22-02-1989 LU 83614 A1 21-01-1982 NL 8104247 A 16-04-1982 SE 452023 B 09-11-1987 US 4408986 A 11-10-1983
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US 5164040	A	17-11-1992	NONE
WO 2016016465	A1	04-02-2016	EP 3175476 A1 07-06-2017 US 2017263475 A1 14-09-2017 WO 2016016465 A1 04-02-2016

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-29

A system, a method of treating a substrate and uses of the system.

1.1. claims: 25(completely); 1-19, 23, 24(partially)

A system and a method of etching a substrate. This invention solves the problem of providing a system and a method for etching a substrate.

1.2. claims: 21, 26(completely); 1-19, 23, 24(partially)

A system and a method of substrate cleaning or for use of thin film cleaning. This invention solves the problem of providing a system and a method for substrate cleaning or for use of thin film cleaning.

1.3. claims: 22, 27-29(completely); 1-19, 23, 24(partially)

A system, use of the system in a thin film deposition process, a method of thin film deposition. This invention solves the problem of providing a system and a method for thin film deposition.

1.4. claims: 20(completely); 1-19(partially)

A system and a method of using the system in an annealing process. This invention solves the problem of providing a system for the use in an annealing process.
