

Cyclic Surface Conditioning Method and Surface Preparation Method for Epitaxial Material Growth

5 Field

The technology relates to the field of surface conditioning and modification, specifically focusing on methods for improving the smoothness and uniformity of various surfaces, such as semiconductor, metal, dielectric, and 2D material surfaces. This field is particularly relevant in industries such as microelectronics, nanotechnology, and advanced materials, where precise control over surface properties is crucial for device performance and functionality.

Background

15 Semiconductor devices and other microelectronic components require extremely smooth surfaces for optimal performance. Surface roughness can lead to various issues, such as defects in the lithography process, reduced device performance, and even device failure. Therefore, achieving a high level of surface smoothness is crucial for the successful fabrication of these components.

Current polishing technologies, such as chemical mechanical polishing (CMP), are widely used to reduce surface roughness on semiconductor wafers and other substrates. CMP involves the use of a chemical slurry and a polishing pad to remove material from the surface, resulting in a smoother surface. However, CMP has limitations in achieving the optimal level of smoothness required for certain lithographical processes, leading to potential failures. Additionally, CMP is not suitable for polishing surfaces with different heights or inclinations, as it can only polish one horizontal plane at a time.

30 Another approach to reduce surface roughness is atomic layer etching (ALE), which involves the removal of material from the surface on an atomic scale. ALE can result in a smoother surface than CMP, but it is not self-stopping and may unnecessarily remove material from different surfaces. Furthermore, ALE processes require the user

to define the time for the smoothening, which can be challenging due to the varying surface conditions.

5 The lithography process itself also contributes to surface roughness, affecting both the original surface and any new surfaces resulting from it, such as sidewalls. The hills and valleys on the wafer surface have different surface energies, making it difficult to develop a process that selectively removes hills without affecting valleys. There is a need for a method that can reduce surface roughness without damaging surfaces that were not reacted with activation gas during cyclic etching.

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In summary, the prior art has several shortcomings, including limitations in achieving optimal surface smoothness, inability to polish surfaces with different heights or inclinations, and lack of selective etching methods. These issues highlight the need for an improved method for surface conditioning that can overcome the limitations of the current technologies and provide a smoother surface for lithographical processes and other microelectronic applications. There is a need for improved methods of surface preparation that can reduce defects and stress in grown materials, particularly for dissimilar materials, to enhance the performance of semiconductor devices and structures. Such methods should ideally be capable of preparing both flat and patterned surfaces, minimizing damage to the surface, and addressing the issue of strain formation due to lattice mismatch between dissimilar materials.

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Summary

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According to a first aspect of the disclosure, a method for surface conditioning based on cyclic processing is provided. The method includes activating a surface, removing excess materials from the surface and surrounding environment, applying a low-energy particle treatment to the surface, and repeating the above steps until the surface has a desired smoothness. Optionally, the low-energy particle treatment uses ions, and may be atomic layer etching (ALE) or atomic layer etching with molecular activation. The cyclic processing may also comprise deposition steps, which can result in an atomic layer deposition (ALD).

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The method may include a combination of etching and deposition, and may involve alternating etching and deposition. The repeating of the steps can be performed until the process has no further effect on different processed surfaces. The method may further comprise ion beam shaping technology and angled particle beam etching.

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The surface treated by the method can be a side wall surface or an inclined surface, and may be selected from the group consisting of semiconductor surfaces, metal surfaces, dielectric surfaces, and 2D material surfaces. The surface can be a patterned surface or a non-patterned surface.

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The activation of the surface may comprise applying a gas exposure to the surface, exposing the surface to a chemical solution, heating the surface to a specific temperature, or applying a particle beam to the surface. The low-energy particle treatment may comprise a low-energy particle beam with a particle energy between 10 eV and 100 eV, or a low-energy plasma treatment with a plasma power between 1 W and 50 W.

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A surface conditioned by the method is also provided.

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According to the second aspect of the disclosure, a method of preparing a surface of a substrate and epitaxial material growth is provided. The method includes exposing the surface to a cyclic removal process to remove impurities and defects from the surface. This process involves modifying a top-most surface layer of the surface by introducing a chemical species, such as halogens, in a process chamber volume enclosing the substrate, to obtain a top-most modified surface layer of the surface. The method also includes evacuating excessive chemical species from the process chamber volume, activating the top-most modified surface layer to form volatile products, and optionally removing etch products from the process chamber volume. The cyclic removal process is followed by epitaxial material growth, wherein the growth material is different from the material of the surface. This method provides a clean and smooth surface for the epitaxial material growth, resulting in high-quality films.

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Optionally, in some examples, the modifying of the top-most surface layer is done in a gas phase that contains only neutral species. This can provide a more controlled and gentle modification process, reducing the risk of damage to the surface.

- 5 Optionally, in some examples, the cyclic removal process has an etch rate per cycle thereof, wherein the etch rate approaches zero as the number of cycles increases. This self-limiting feature ensures that the process does not over-etch the surface, preserving the desired surface properties.
- 10 Optionally, in some examples, the activation of the top-most modified surface layer is done in a gas phase that does not involve surface bombardment with ions. This can help to maintain a damage-free surface, which is crucial for the subsequent epitaxial material growth.
- 15 According to the third aspect of the disclosure, the method includes a step of a deposition process to overgrow impurities and defects on the surface, comprising modifying the top-most surface layer by introducing a chemical species in the process chamber volume for said overgrow. This additional step can help to further improve the surface quality and ensure a smooth and defect-free surface for the epitaxial material
- 20 growth.

- Optionally, in some examples, the step of the deposition process is preceding the cyclic removal process, or the step of the deposition process is succeeding the cyclic removal process. This flexibility in the order of the steps allows for optimization of the process
- 25 depending on the specific substrate and growth material.

- Optionally, in some examples, the chemical species for said overgrow comprises gallium, nitrogen, and optionally aluminum. These elements can be used to form a variety of compound semiconductor materials, such as III-nitride materials, which have
- 30 numerous applications in optoelectronics and power electronics.

Optionally, in some examples, the deposition process is cyclic. This can provide a more controlled and uniform deposition process, ensuring a high-quality overgrowth layer.

Optionally, in some examples, the deposition process has a deposition rate per cycle thereof, wherein the deposition rate approaches zero as the number of cycles increases. This self-limiting feature ensures that the process does not over-deposit the material, preserving the desired surface properties.

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Optionally, in some examples, at least one of the steps includes a self-limiting reaction that slows down or stops as a function of time or, equivalently, as a function of species dosage. This can help to ensure a controlled and precise process, avoiding over-etching or over-deposition of the material.

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Optionally, in some examples, the self-limiting reaction comprises chemisorption, deposition, extraction, and/or conversion such as oxidation or nitridation. These types of reactions can provide a controlled and gentle process, reducing the risk of damage to the surface.

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Optionally, in some examples, the method includes an additional passivation step preceding the epitaxial material growth to avoid surface oxidation or contamination prior to the material growth. This can help to further improve the surface quality and ensure a clean and defect-free surface for the epitaxial material growth.

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Optionally, in some examples, the surface comprises a pattern, such as regularly arranged holes, lines, and/or pillars. This can provide additional control over the properties of the epitaxial material growth, such as strain relaxation and defect reduction.

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Optionally, in some examples, the method includes retrieving process control information, such as information from optical emission and residual gas analysis, wherein process parameters of the method are adjusted based on the process control information. This can help to optimize the process in real-time, ensuring the best possible surface quality and epitaxial material growth.

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According to the fourth aspect of the disclosure, a method for epitaxial material growth on a surface of a substrate is provided, comprising a cyclic process including a sequence of any of the steps according to the second aspect of the disclosure, followed

by any of the steps according to the third aspect of the disclosure. The method includes repeating the sequence a plurality of times, epitaxial material growth of a growth material on the surface, and wherein the growth material is different from the material of the surface. This method can provide a highly controlled and optimized process for preparing the surface and growing high-quality epitaxial materials.

Optionally, in some examples, the steps are repeated until at least one of said steps has no further effect on the surface. This can help to ensure that the surface is fully prepared and optimized for the epitaxial material growth, resulting in high-quality films.

Brief Description of the Drawings

Examples are described in more detail below with reference to the appended drawings.

Figure 1 shows an example of the surface conditioning method based on cyclic processing.

Figure 2 shows another example of the surface conditioning method based on cyclic processing.

Figure 3 shows another example of the surface conditioning method based on cyclic processing.

Figure 4 is a flowchart illustrating the method for surface conditioning based on cyclic processing according to an example of the present disclosure.

Figure 5 is an atomic force microscopy (AFM) micrograph of the initial surface and a final surface after the cyclic process according to an example.

Figure 6 is a schematic illustrating the effect of a cyclic removal process for preparing substrate surfaces for improved material growth, comparing material growth on a typical surface and material growth after a cyclic removal process.

Figure 7 is a schematic illustrating the effect of a deposition process followed by a cyclic removal process for preparing substrate surfaces for improved material growth, comparing material growth on a typical surface and material growth after material deposition and the following cyclic removal process.

Figure 8 is a schematic illustrating the effect of a cyclic removal and deposition process for preparing substrate surfaces for improved material growth, comparing material

growth on a typical surface and material growth after the cyclic removal and deposition process.

Figure 9 is a block diagram illustrating an execution process flow of a method of a cyclic process for preparing substrate surfaces for improved material growth.

5 Figure 10 shows Atomic force microscopy (AFM) micrographs and line scans of the initial Si surface and the surface after cyclic etching, demonstrating the reduction in roughness after the cyclic etch process.

Figure 11 shows Atomic force microscopy (AFM) micrographs of the initial GaN surface and the surface after cyclic deposition followed by cyclic etching, demonstrating the
10 reduction in roughness after the cyclic deposition process followed by the cyclic etch process.

Detailed Description

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A. Cyclic Surface Conditioning

The detailed description set forth below provides information and examples of the disclosed technology with sufficient detail to enable those skilled in the art to practice
20 the disclosure.

Figure 1 shows an example of the surface conditioning method based on cyclic processing. In Figure 1a, a substrate 100 with an initial surface roughness 110 is illustrated. The substrate 100 can be made of various materials, such as
25 semiconductor materials, metal materials, dielectric materials, or 2D materials. The surface of the substrate 100 can be patterned or non-patterned.

In Figure 1b, the final surface is shown, where the substrate 100 has a desired surface 111 with reduced surface roughness while preserving the original thickness of the
30 substrate 100. This reduction in surface roughness is achieved through the cyclic processing method, which includes activating the surface, removing excess materials, applying a low-energy particle treatment, and repeating these steps until the desired smoothness is achieved. This surface conditioning is achieved through the cyclic

processing method as described earlier, which can involve any cyclic process, including atomic layer etching (ALE) or atomic layer deposition (ALD).

Figure 2 shows another example of the surface conditioning method based on cyclic processing. In Figure 2a, the initial structure 110 with surfaces 111, 112, and 122, which have roughness, is illustrated. In addition, substrate 100 has another feature 210, with a different height than 110. The feature 210 has different surfaces, 211, 212, and 222 with roughness as illustrated.

In Figure 2b, the final structure is shown, with feature 110 having the desired surfaces 311, 312, and 322 and reduced surface roughness of features 110 while preserving the original dimensions of the features 110. Furthermore, Figure 2b shows feature 210 with the desired surfaces 411, 412, and 422 and reduced surface roughness of features 210 while preserving the original critical dimensions of the features 210. This surface conditioning is achieved through the cyclic processing method as described earlier, which can involve any cyclic process, including atomic layer etching (ALE) or atomic layer deposition (ALD).

Figure 3 shows another example of the surface conditioning method based on cyclic processing. In Figure 3a, the initial structure 110 with surfaces 111, 112, and 122, which have roughness, is illustrated.

In Figure 3b, the final structure is shown, with the desired surfaces 222, 212, and 211 and reduced surface roughness of features 110 while preserving the original critical dimensions of the features 110. This surface conditioning is achieved through the cyclic processing method as described earlier, which can involve any cyclic process, including atomic layer etching (ALE) or atomic layer deposition (ALD).

Figure 4 is a flowchart illustrating the method for surface conditioning based on cyclic processing according to an example of the present disclosure. The method includes activating the surface (step 401), removing excess materials from the chamber (step 402), applying a low-energy particle treatment to the surface (step 403), and repeating the above steps until the surface has the desired smoothness (step 404). The low-energy particle treatment can be etching, deposition, or a combination of both. The

method can also include ion beam shaping technology and angled particle beam etching.

Figure 5 shows atomic force microscopy (AFM) micrographs of the initial surface and a final surface after the cyclic process according to an example. In Figure 5a, a micrograph of the scan area 500 is shown, with an area of about $1 \mu\text{m}^2$. In the bottom graph, the roughness values 501, 502, and 503 are measured in different places of the scan area, top, middle, and bottom, respectively. The roughness is measured to be around 0.11 nm.

In Figure 5b, results from AFM measurement of the final surface are shown. The top part, 504, shows a micrograph of the scan area, where the area is about $1 \mu\text{m}^2$. In the bottom graph, the roughness values 505, 506, and 507 are measured in different places of the scan area, top, middle, and bottom, respectively. The roughness is measured to be around 0.021 nm. This reduction in surface roughness is achieved through the cyclic processing method as described earlier, which can involve any cyclic process, including atomic layer etching (ALE) or atomic layer deposition (ALD).

A1. Surface Activation Process

The surface activation process is a step in the surface conditioning method based on cyclic processing. In this process, the surface of a substrate is activated to facilitate the subsequent low-energy particle treatment, which can be etching, deposition, or a combination of both. The activation process can be performed using various techniques, such as gas exposure, chemical solution exposure, temperature-based activation, and particle beam activation. Each of these techniques has its advantages and can be tailored to suit the specific requirements of the substrate material and the desired surface smoothness.

A1.1. Gas Exposure Activation

In some examples, the surface activation process may comprise exposing the surface to a gas or a mixture of gases. The gas exposure can modify the surface chemistry, making it more susceptible to the low-energy particle treatment. The selection of

appropriate gases is to achieve the desired surface activation and ensure compatibility with the substrate material.

A1.2. Chemical Solution Activation

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In some examples, the surface activation process may comprise exposing the surface to a chemical solution. The chemical solution can interact with the surface material, altering its properties and making it more amenable to the low-energy particle treatment. The selection of appropriate chemical solutions is crucial to achieve the
10 desired surface activation and ensure compatibility with the substrate material.

A1.3. Temperature-Based Activation

In some examples, the surface activation process may comprise heating the surface
15 to a specific temperature or within a specific temperature range. The temperature-based activation can cause thermal expansion or contraction of the surface material, leading to changes in the surface properties that can facilitate the low-energy particle treatment. The determination of the optimal temperature range is essential to achieve the desired surface activation and ensure compatibility with the substrate material.

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A1.3.1. Determining Optimal Temperature Range

The optimal temperature range for the temperature-based activation process depends on the substrate material and the desired surface properties. In some examples, the
25 temperature range may be selected to cause thermal expansion or contraction of the surface material, leading to changes in the surface roughness or other properties that can facilitate the low-energy particle treatment. In other examples, the temperature range may be selected to induce phase transitions or other structural changes in the surface material, which can alter its properties and make it more amenable to the low-
30 energy particle treatment. The determination of the optimal temperature range can be based on factors such as the thermal properties of the substrate material, the desired surface properties, and the compatibility of the temperature range with the low-energy particle treatment process.

A1.4. Particle Beam Activation

In some examples, the surface activation process may comprise applying a particle beam to the surface. The choice of particle beams for the particle beam activation process depends on the substrate material and the desired surface properties. In some examples, the particle beams may include ions, electrons, or neutral particles that can physically sputter or chemically react with the surface material to modify its properties. In other examples, the particle beams may include photons or other electromagnetic radiation that can induce electronic or vibrational excitations in the surface material, leading to changes in the surface properties that can facilitate the low-energy particle treatment. The selection of appropriate particle beams can be based on factors such as the reactivity of the particles with the substrate material, the desired surface properties, and the compatibility of the particle beams with the low-energy particle treatment process.

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A2. Excess Material Removal Process

In one example, the excess material removal process is a step in the surface conditioning method based on cyclic processing. This process aims to remove any excess materials from the surface and the surrounding environment after the surface activation process. The removal of excess materials ensures that the subsequent low-energy particle treatment can be effectively applied to the surface without interference from unwanted materials. The excess material removal process may comprise various techniques, such as purging gases, pumping out gases, or a combination of pumping and purging.

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A2.1. Purging Gases

In some examples, the excess material removal process may comprise purging gases. Purging gases involve introducing an inert gas, such as nitrogen or argon, into the processing chamber to displace and remove any excess materials, including reactive gases or byproducts from the surface activation process. The purging gas may be introduced at a controlled flow rate and pressure to ensure efficient removal of excess materials without causing damage to the surface or altering the surface properties. The

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use of purging gases in the excess material removal process offers the advantage of a simple and cost-effective technique for removing unwanted materials from the processing environment.

5 A2.2. Pumping Out Gases

In other examples, the excess material removal process may comprise pumping out gases. Pumping out gases involves using a vacuum pump to evacuate the processing chamber, thereby removing any excess materials, including reactive gases or byproducts from the surface activation process. The vacuum pump may be operated at a controlled pressure and flow rate to ensure efficient removal of excess materials without causing damage to the surface or altering the surface properties. The use of pumping out gases in the excess material removal process offers the advantage of a more thorough removal of unwanted materials from the processing environment compared to purging gases alone.

A2.3. Combination of Pumping and Purging

In some examples, the excess material removal process may comprise a combination of pumping and purging. This approach involves using both a vacuum pump to evacuate the processing chamber and an inert gas to displace and remove any excess materials, including reactive gases or byproducts from the surface activation process. The combination of pumping and purging may be performed in a sequential or simultaneous manner, depending on the specific requirements of the surface conditioning process. The use of a combination of pumping and purging in the excess material removal process offers the advantage of a more comprehensive removal of unwanted materials from the processing environment, ensuring that the subsequent low-energy particle treatment can be effectively applied to the surface without interference from excess materials.

The excess material removal process may be tailored to suit the specific requirements of the surface conditioning process, taking into account factors such as the type of surface being treated, the materials involved in the surface activation process, and the desired surface smoothness. By effectively removing excess materials from the

surface and the surrounding environment, the excess material removal process plays a role in achieving the desired surface smoothness and ensuring the overall success of the surface conditioning method based on cyclic processing.

5 A3. Low-Energy Particle Treatment

In one example, the surface conditioning method based on cyclic processing includes a low-energy particle treatment step. This low-energy particle treatment can be applied to various types of surfaces, such as patterned and non-patterned surfaces, and can
10 be used for different materials, including semiconductor surfaces, metal surfaces, dielectric surfaces, and 2D material surfaces. The low-energy particle treatment can be performed using a low-energy particle beam with a particle energy between 10 eV and 100 eV, or a low-energy plasma treatment with a plasma power between 1 W and 50 W.

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A3.1. Low-Energy Particle Etching

In some examples, the low-energy particle treatment may comprise a low-energy particle etching process. This etching process can be used to selectively remove
20 material from the surface, thereby reducing surface roughness and improving the overall surface quality. The low-energy particle etching process can be performed using various techniques, such as ion beam etching, reactive ion etching, or plasma etching.

25 A3.1.1. Atomic Layer Etching (ALE) with Molecular Activation

In one example, the low-energy particle etching process may comprise atomic layer etching (ALE) with molecular activation. ALE with molecular activation is a highly controlled etching process that allows for the removal of material at the atomic level,
30 resulting in a very smooth surface. This process involves the activation of the surface using a suitable activation method, such as gas exposure, chemical solution exposure, heating, or particle beam exposure, followed by the application of a low-energy particle beam or plasma treatment to selectively remove material from the surface. The use of ALE with molecular activation can provide several advantages, such as improved

control over the etching process, reduced surface roughness, and minimal damage to the underlying material.

A3.2. Low-Energy Particle Deposition

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In some examples, the low-energy particle treatment may comprise a low-energy particle deposition process. This deposition process can be used to selectively deposit material onto the surface, thereby filling in any surface irregularities and improving the overall surface quality. The low-energy particle deposition process can be performed using various techniques, such as atomic layer deposition (ALD), chemical vapor deposition (CVD), or physical vapor deposition (PVD).

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A3.2.1. Atomic Layer Deposition (ALD)

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In one example, the low-energy particle deposition process may comprise atomic layer deposition (ALD). ALD is a highly controlled deposition process that allows for the deposition of material at the atomic level, resulting in a very smooth surface. This process involves the sequential exposure of the surface to different precursor gases, which react with the surface to form a thin layer of the desired material. The use of ALD can provide several advantages, such as improved control over the deposition process, reduced surface roughness, and the ability to deposit materials with high conformality and uniformity.

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A3.3. Combination of Etching and Deposition

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In some examples, the low-energy particle treatment may comprise a combination of etching and deposition processes. This can involve alternating between etching and deposition steps, or performing both etching and deposition simultaneously. The combination of etching and deposition can be used to selectively remove material from certain areas of the surface while depositing material in other areas, thereby reducing surface roughness and improving the overall surface quality.

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A3.3.1. Alternating Etching and Deposition

In one example, the low-energy particle treatment may comprise alternating etching and deposition steps. This can involve performing an etching step to selectively remove material from the surface, followed by a deposition step to selectively deposit material onto the surface. By alternating between etching and deposition steps, the surface roughness can be reduced while maintaining the overall thickness of the material. This approach can provide several advantages, such as improved control over the surface conditioning process, reduced surface roughness, and the ability to selectively modify the surface without affecting the underlying material.

10 A4. Cyclic Processing and Surface Smoothness

In one example, the cyclic processing and surface smoothness section focuses on determining the desired surface smoothness, implementing a self-stopping cyclic process, and monitoring the reduction of surface roughness during the surface conditioning process. The cyclic processing method may comprise various optional features to achieve the desired surface smoothness and reduce surface roughness effectively.

20 A4.1. Determining Desired Surface Smoothness

In some examples, the desired surface smoothness is determined based on the specific application or requirements of the processed substrate. The surface smoothness may be quantified using various surface roughness parameters, such as root-mean-square (RMS) roughness, average roughness, or peak-to-valley roughness. The desired surface smoothness may be achieved by repeating the cyclic processing steps until the surface roughness parameters reach the predetermined values or meet the specific requirements for the processed substrate.

30 A4.2. Self-Stopping Cyclic Process

In one example, the cyclic processing method may comprise a self-stopping feature, where the process automatically stops when it has no further effect on the surface or when the surface roughness parameters reach a plateau. This self-stopping feature may be advantageous in preventing over-processing of the surface and preserving the

original dimensions of the substrate or patterned features. The self-stopping cyclic process may be achieved by optimizing the process parameters, such as activation conditions, excess material removal methods, and low-energy particle treatment conditions, to ensure that the process has minimal or no impact on the surface once
5 the desired smoothness is achieved.

A4.3. Monitoring Surface Roughness Reduction

In some examples, the surface roughness reduction during the cyclic processing may
10 be monitored using various in-situ or ex-situ metrology techniques. The in-situ metrology techniques may include optical monitoring, ellipsometry, or reflectometry, which can provide real-time feedback on the surface roughness parameters during the cyclic processing. The ex-situ metrology techniques may include atomic force
15 microscopy (AFM), scanning electron microscopy (SEM), or transmission electron microscopy (TEM), which can provide high-resolution images and quantitative measurements of the surface roughness parameters after the cyclic processing.

The monitoring of surface roughness reduction may be advantageous in determining the progress of the surface conditioning process and ensuring that the desired surface
20 smoothness is achieved. Additionally, the monitoring may provide valuable information for optimizing the process parameters and improving the efficiency of the cyclic processing method.

A5. Integration with Ion Beam Shaping Technology

25 In one example, the surface conditioning method based on cyclic processing can be integrated with ion beam shaping technology to further enhance the surface smoothing process. Ion beam shaping technology can be used to modify the surface topography by controlling the ion beam parameters, such as ion energy, ion species, ion incidence
30 angle, and ion flux. This integration can provide additional control over the surface conditioning process, enabling more precise and efficient surface smoothing.

A5.1. Angled Particle Beam Etching

In some examples, the integration of ion beam shaping technology with the surface conditioning method may comprise angled particle beam etching. Angled particle beam etching can be used to selectively remove material from specific areas of the surface, such as the peaks of surface roughness features, while preserving the valleys.

5 This can result in a more uniform surface topography and reduced surface roughness.

In one example, the angled particle beam etching can be performed by directing an ion beam at an angle relative to the surface normal. The angle can be adjusted to optimize the etching process for the specific surface features and material properties.

10 By controlling the ion beam parameters, such as ion energy, ion species, ion incidence angle, and ion flux, the etching process can be tailored to achieve the desired surface smoothing effect.

A5.2. Optimizing Ion Beam Parameters

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In some examples, the ion beam parameters can be optimized to achieve the desired surface conditioning effect. The ion beam parameters can include ion energy, ion species, ion incidence angle, and ion flux. By adjusting these parameters, the ion beam shaping technology can be tailored to the specific surface features and material properties, resulting in more efficient and precise surface smoothing.

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In one example, the ion energy can be adjusted to control the penetration depth of the ions into the surface material. Higher ion energies can result in deeper penetration and more aggressive etching, while lower ion energies can result in shallower penetration and more gentle etching. The optimal ion energy can depend on the specific surface features and material properties, as well as the desired surface smoothing effect.

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In another example, the ion species can be selected based on the chemical reactivity with the surface material. Some ion species may be more effective at etching certain materials, while others may be less effective or even cause unwanted side effects, such as surface damage or contamination. The optimal ion species can depend on the specific surface features and material properties, as well as the desired surface smoothing effect.

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In yet another example, the ion incidence angle can be adjusted to control the directionality of the etching process. By directing the ion beam at an angle relative to the surface normal, the etching process can be made more selective, preferentially removing material from specific areas of the surface, such as the peaks of surface roughness features. The optimal ion incidence angle can depend on the specific surface features and material properties, as well as the desired surface smoothing effect.

In still another example, the ion flux can be adjusted to control the etching rate and uniformity. Higher ion fluxes can result in faster etching and more aggressive surface smoothing, while lower ion fluxes can result in slower etching and more gentle surface smoothing. The optimal ion flux can depend on the specific surface features and material properties, as well as the desired surface smoothing effect.

By optimizing the ion beam parameters, the integration of ion beam shaping technology with the surface conditioning method based on cyclic processing can provide more precise and efficient surface smoothing, resulting in improved surface quality and reduced surface roughness. This integration can be particularly advantageous for applications requiring high-quality surfaces, such as semiconductor devices, optical components, and other advanced technologies.

A6. Surface Conditioning for Various Surface Types

The surface conditioning method based on cyclic processing can be applied to various surface types, including patterned surfaces and non-patterned surfaces, as well as surfaces made of different materials such as semiconductor materials, metal materials, dielectric materials, and 2D materials. The method can be tailored to address the specific requirements of each surface type and material, providing a versatile and efficient approach to surface conditioning.

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A6.1. Patterned Surfaces

In some examples, the surface conditioning method can be applied to patterned surfaces, which may comprise features such as lines, dots, pillars, vias, grids, and

other patterns. The method can be adapted to address the specific challenges associated with conditioning patterned surfaces, such as preserving the original dimensions of the features while reducing surface roughness.

5 A6.1.1. Side Wall Surfaces

In one example, the surface conditioning method can be applied to side wall surfaces of patterned features. The method can be tailored to address the specific challenges associated with conditioning side wall surfaces, such as maintaining the original
10 dimensions of the features while reducing surface roughness. The cyclic processing method, including activation, removal of excess materials, and low-energy particle treatment, can be optimized to achieve the desired surface smoothness on side wall surfaces without affecting the overall dimensions of the patterned features.

15 A6.1.2. Inclined Surfaces

In some examples, the surface conditioning method can be applied to inclined surfaces of patterned features. The method can be adapted to address the specific challenges associated with conditioning inclined surfaces, such as maintaining the original
20 dimensions of the features while reducing surface roughness. The cyclic processing method, including activation, removal of excess materials, and low-energy particle treatment, can be optimized to achieve the desired surface smoothness on inclined surfaces without affecting the overall dimensions of the patterned features.

25 A6.2. Non-Patterned Surfaces

In one example, the surface conditioning method can be applied to non-patterned surfaces, such as the surface of a substrate 100. The method can be tailored to address the specific challenges associated with conditioning non-patterned surfaces,
30 such as reducing surface roughness without affecting the overall thickness of the substrate. The cyclic processing method, including activation, removal of excess materials, and low-energy particle treatment, can be optimized to achieve the desired surface smoothness on non-patterned surfaces while preserving the original thickness of the substrate.

A6.3. Material-Specific Surface Conditioning

The surface conditioning method based on cyclic processing can be adapted to
5 address the specific requirements of different materials, such as semiconductor
materials, metal materials, dielectric materials, and 2D materials. In some examples,
the activation process, removal of excess materials, and low-energy particle treatment
can be tailored to the specific material properties and requirements, ensuring optimal
surface conditioning results.

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For example, the selection of appropriate gases, chemical solutions, temperature
ranges, and particle beams for the activation process can be based on the specific
material properties and requirements. Similarly, the selection of appropriate low-
energy particle treatments, such as etching or deposition processes, can be tailored to
15 the specific material properties and requirements.

By adapting the surface conditioning method to the specific material properties and
requirements, the method can provide efficient and effective surface conditioning
results for various surface types and materials, ensuring optimal performance and
20 reliability of the conditioned surfaces.

B. Surface Preparation Method for Epitaxial Material Growth

Figure 6 shows a schematic illustrating the effect of a cyclic removal process for
25 preparing substrate surfaces (Si, Sapphire, SiC, GaN, or any substrates) for improved
material growth. On the left side, material growth on a typical surface 2200 of a
substrate 2100 is shown. On the right side, material growth after a cyclic removal
process is shown, which results in a prepared substrate surface 2201. The grown
material 2301 is improved by reducing defects compared to the grown material 2300.

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Figure 7 displays a schematic illustrating the effect of a deposition process followed by
a cyclic removal process for preparing substrate surfaces (Si, Sapphire, SiC, GaN, or
any substrates) for improved material growth. On the left side, material growth on a
typical surface 2200 of a substrate 2100 is shown. On the right side, material growth

after material deposition 2400 and the following cyclic removal process is shown, resulting in a prepared substrate surface 2202. The grown material 2302 is improved by reducing defects compared to the grown material 2300.

- 5 Figure 8 presents a schematic illustrating the effect of a cyclic removal and deposition process for preparing substrate surfaces (Si, Sapphire, SiC, GaN, or any substrates) for improved material growth. On the left side, material growth on a typical surface 2200 of a substrate 2100 is shown. On the right side, the cyclic removal and deposition process provides a substrate surface 2204 for material growth. The intermediate
10 flattened surface 2203 of the substrate and the material deposition 2401 are also shown. The grown material 2303 is improved by reducing defects compared to the grown material 2300.

- Figure 9 is a block diagram illustrating an execution process flow of a method of a
15 cyclic process for preparing substrate surfaces for improved material growth.

- Figure 10 shows Atomic force microscopy (AFM) micrographs and line scans of the initial Si surface (Left) and the surface after cyclic etching (Right). The top parts, 2500 and 2504, display a micrograph of the scan area, where the area is 1 μm^2 . The bottom
20 graphs 2501, 2502, 2503, 2505, 2506, and 2507 are line scans in different places of the corresponding scan areas 2500 and 2504: top, middle, and bottom, respectively. The roughness is substantially reduced after the cyclic etch process.

- Figure 11 presents Atomic force microscopy (AFM) micrographs of the initial GaN
25 surface (Left) and the surface after cyclic deposition followed by cyclic etching (Right). The roughness is substantially reduced after the cyclic deposition process followed by the cyclic etch process.

- Further discussion of the surface preparation for epitaxial material growth in relation to
30 figures 6 – 11 are provided below under sections 6 to 8.

B2. Substrate material

In some examples, the material of the surface can be silicon (Si), sapphire, silicon carbide (SiC), gallium nitride (GaN), or any other suitable substrate material. The choice of the surface material can significantly impact the quality of the grown material and the effectiveness of the cyclic removal process. The surface may have various materials and patterns, which can affect the growth of the material. In some examples, the surface of the substrate may comprise a pattern, such as regularly arranged holes, lines, and/or pillars. The disclosed method can be applied to these patterned surfaces, allowing for the preparation of substrate surfaces with various geometries and topographies. The method may be adapted to accommodate various surface patterns to ensure optimal material growth.

B3. Surface preparation method

B3.1. Cyclic Removal Process

In one example, the cyclic removal process involves exposing the surface of a substrate to a series of steps that remove impurities and defects from the surface. This process can be repeated multiple times to achieve the desired surface quality.

B3.1.1. Modifying the Top-Most Surface Layer

The top-most surface layer of the substrate is modified by introducing a chemical species, such as halogens, in a process chamber volume enclosing the substrate. The process chamber volume is an enclosed space where the substrate is exposed to the chemical species and the cyclic removal process takes place. The halogens may be chlorine, bromine, or iodine. The chemical species chemisorbs to the surface. This results in the formation of a top-most modified surface layer on the substrate. The modification step forms a thin reactive surface layer with a well-defined thickness that is subsequently more easily removed than the unmodified material. The modified layer is characterized by a sharp gradient in chemical composition. The speed of chemisorption can be increased by activating the chemical species, for example, with a plasma. The modifying of the top-most surface layer can be a self-limiting process, which slows down or stops as a function of time or, equivalently, as a function of species dosage.

In some examples, excessive chemical species may be evacuated from the process chamber volume after modifying the top-most surface layer. This evacuation can be done using an inert gas, ensuring that the process chamber volume is free from
5 unwanted chemical species that may interfere with the cyclic removal process.

B3.1.2. Activating the Top-Most Modified Surface Layer

The top-most modified surface layer is activated to form volatile products. The
10 activation removes the thin reactive surface layer resulting from the previous surface modification step. This activation can be done in a gas phase that does not involve surface bombardment with ions, such as by temperature cycling, light pulse exposure, and/or chemical reactions. By excluding surface bombardment by energetic particles in the cyclic removal process, the formation of a damage-free surface can be ensured,
15 providing an optimal surface for epitaxial material growth. The activation of the top-most modified surface layer can be a self-limiting process, which slows down or stops as a function of time or, equivalently, as a function of species dosage.

In some examples, the activation of the top-most modified surface layer may comprise
20 a plasma pulse step, with low ion energies for the plasma pulse, such as ion energies below 60 eV. Ion energies around 20 eV provides in some examples a particularly advantageous result. The use of low ion energies ensures a low-damage etching of the surface, resulting in a damage-free surface that is optimal for epitaxial material growth.

25 In some examples, etch products may be removed from the process chamber volume after activating the top-most modified surface layer. This removal ensures that the process chamber volume is free from etch products that may interfere with the subsequent steps of the method, such as epitaxial material growth.

30 The surface modification and the activation steps provide an atomic layer etching process. The atomic layer etching process may further comprise quasi-atomic layer etching processes, which may include quasi-self-limiting reactions and non-self-limiting reactions. Isotropic atomic layer etching processes, which use thermal

desorption and chemical reactions, are in some examples especially advantageous and provide optimized results for surface preparation before material growth.

The method of preparing a surface of a substrate and epitaxial material growth may
5 comprise various optional features and steps, such as a deposition process to overgrow impurities and defects on the surface, a passivation step preceding the epitaxial material growth, and the use of self-limiting reactions in the cyclic removal process. These optional features can further enhance the effectiveness of the method and improve the quality of the grown material, and are described in more detail below.

10

B3.1.3. Number of cycles and Etch Rate per Cycle

The number of cycles in the cyclic removal process can be optimized based on the roughness of the surface. The number of cycles is in the range of 5 to 200 cycles in
15 one example. For instance, 20 cycles may provide a particularly optimal surface for material growth.

In some examples, the cyclic removal process has an etch rate per cycle, wherein the etch rate approaches zero as the number of cycles increases, indicating that the
20 process becomes self-limiting as a function of time or species dosage. This allows for a facilitated process in controlling the amount of material removed from the surface, ensuring a smooth and defect-free surface for subsequent material growth.

The cyclic removal process can be combined with ion beam shaping processes to
25 smoothen and clean different faces of structured surfaces, such as surfaces with patterns like regularly arranged holes, lines, and/or pillars. This can further enhance the quality of the grown material and expand the potential applications of the method.

B3.2. Deposition Process

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In some examples, the method may comprise a deposition process to overgrow impurities and defects on the surface. This process involves modifying the top-most surface layer by introducing a chemical species in the process chamber volume for the overgrow. The chemical species for the overgrow can comprise gallium, nitrogen, and

optionally aluminum. The deposition process may comprise quasi-atomic layer deposition processes, which may include quasi-self-limiting reactions and non-self-limiting reactions.

5 B3.2.1. Overgrowing Impurities and Defects

In some examples, the deposition process provides an interface layer by depositing a thin film material on the surface. This interface layer can relax the strain caused by lattice mismatch of dissimilar materials in contact with each other, alleviating the lattice mismatch problem with the material subsequently grown by epitaxy. The deposition process can also fill valleys on the surface, ensuring that the surface remains smooth even during the subsequent epitaxial growth of very thin films.

The deposition process may precede or succeed the cyclic removal process, depending on the desired surface quality and material growth requirements. In some cases, an additional passivation step may be performed before the epitaxial material growth to avoid surface oxidation or contamination prior to the material growth. This can further improve the quality of the grown material.

20 B3.2.2. Chemical Species for Overgrow

In some examples, the chemical species for the overgrow can comprise gallium, nitrogen, and optionally aluminum. The deposition process can involve forming a monolayer of gallium atoms, followed by forming an atomic layer of gallium nitride on the surface.

B3.2.3. Cyclic Deposition Process

In some examples, the deposition process can be cyclic, with the deposition rate approaching zero as the number of cycles increases. This allows for a facilitated control over the thickness of the deposited material and ensures a smooth and defect-free surface for subsequent material growth. The deposition process can be a self-limiting process as a function of time or species dosage, as described in further detail below.

The number of cycles in the deposition process can be optimized based on the roughness of the surface. The number of cycles is in the range of 5 to 200 cycles in one example. For instance, 20 cycles may provide a particularly optimal surface for material growth.

B4. Cyclic Process and subsequent Epitaxial Material Growth

In some examples, the method may involve a sequence of steps in the cyclic process, including any of the steps described in sections 3.1 and 3.2. The total sequence can be repeated a plurality of times to achieve an optimized surface quality and prepare the surface for epitaxial material growth. The growth of high-quality films of various materials on the prepared substrate surface is provided.

In some examples, the total sequence of steps in the cyclic process may be repeated a plurality of times to achieve an optimized surface quality. The number of cycles can be optimized based on the roughness of the surface, with a range of 5 to 200 cycles being possible. For instance, 20 cycles may provide a particularly optimal surface for material growth.

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Thus, following the cyclic process, epitaxial material growth is performed on the prepared surface of the substrate. This involves forming a high-quality film of the growth material on the substrate surface. The growth material is different from the material of the surface, and in some examples, it may be a III-Nitride material grown on a silicon substrate.

25

The cyclic process can be integrated with growth techniques, such as molecular beam epitaxy (MBE) or metal-organic chemical vapor deposition (MOCVD), providing the surface preparation in the same chamber, alternatively, in a neighboring chamber without exposure to ambient air in between the surface preparation and the growth process, which additionally improves the quality of the grown films. The method can also be combined with other processes such as atomic layer cleaning, rapid surface temperature cycling, and self-organization, to further enhance the quality of the grown material.

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The method may comprise retrieving process control information, such as information from optical emission and residual gas analysis, and adjusting process parameters of the method based on the process control information. This can help optimize the process for different substrates and surface patterns, resulting in improved material growth. I.e. monitoring and control of the cyclic process are used to adjust the process parameters as required for the desired outcome. In situ control is preferred and typically includes monitoring of such parameters as optical emission, residual gas analysis, and monitoring thin film properties in various ways, for instance, with light interferometry. By monitoring these parameters, the process endpoint and intermediate process points can be determined, and the process time and process parameters adjusted as necessary to achieve the improved and prepared surface for material growth.

15 B5. Self-Limiting Reactions

In some examples, the method may comprise at least one self-limiting reaction that slows down or stops as a function of time or, equivalently, as a function of species dosage. These self-limiting reactions can provide a controlled and precise process for modifying the surface layer and activating the top-most modified surface layer, as well as providing a controlled and precise deposition process in some examples, ensuring a consistent and high-quality surface preparation for epitaxial material growth.

Processes in the prior art, such as in GB2601404A, does not stop after the removal of the uneven damaged surface layers and will etch underlying originally damage-free layers. This may be a big disadvantage for smoothening very thin films and structures for which the removal of a few additional nanometers of material may be critical and unwanted. Chemical mechanical polishing or planarization (CMP) processes also do not stop after the removal of the uneven damaged surface layers and will remove some underlying originally damage-free layers.

In one example, the self-limiting reaction may comprise chemisorption, where a chemical species chemisorbs to the surface. In some examples, the self-limiting reaction may comprise deposition, where a chemical species is introduced to the

process chamber volume for overgrowing impurities and defects on the surface. In one example, the self-limiting reaction may comprise extraction. In the extraction case, the original material is a compound of elements, and the surface modification step removes one element preferentially from the surface, while a different element is removed in the subsequent activation/removal step. This extraction process can be self-limiting, slowing down or stopping as a function of time or species dosage. The controlled extraction process can provide a consistent and damage-free removal of the top-most modified surface layer, providing a clean and smooth surface for epitaxial material growth. In some examples, the self-limiting reaction may comprise conversion, such as oxidation or nitridation, where the chemical species introduced to the process chamber volume reacts with the surface to form a modified surface layer. This conversion process can be self-limiting, slowing down or stopping as a function of time or species dosage. The controlled conversion process can provide a consistent and precise modification of the surface layer, providing an optimal surface for epitaxial material growth.

B6. Examples of process steps in different orders

In this section, various examples of the disclosed method for preparing substrate surfaces for improved material growth are described. These examples illustrate different configurations and sequences of the method steps, which can be tailored to specific applications and requirements.

B6.1. Deposition Process Preceding Cyclic Removal Process

In one example, the deposition process precedes the cyclic removal process. This configuration can be advantageous in certain situations, as it allows for the formation of an interface layer by depositing a thin film material on the substrate surface before the cyclic removal process. The interface layer can help relax the strain caused by lattice mismatch between dissimilar materials in contact with each other, alleviating the lattice mismatch problem with the material subsequently grown by epitaxy. This embodiment is illustrated in Figure 7, where the material deposition 2400 is followed by the cyclic removal process, resulting in a prepared substrate surface 2202.

B6.2. Deposition Process Succeeding Cyclic Removal Process

In another example, the deposition process succeeds the cyclic removal process. This configuration can be advantageous in certain situations, as it allows for the overgrowth
5 of impurities and defects on the surface after the cyclic removal process. The deposition process can fill the valleys on the surface, ensuring that the surface remains smooth even during the subsequent epitaxial growth of very thin films. This embodiment is illustrated in Figure 8, where the cyclic removal process is followed by the material deposition 2401, resulting in a prepared substrate surface 2204.

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B6.3. Passivation Step Preceding Epitaxial Material Growth

In some examples, the method may comprise an additional passivation step preceding the epitaxial material growth. This can further enhance the quality of the grown material
15 by protecting the prepared surface from unwanted reactions with ambient gases or contaminants. E.g. the passivation step can be advantageous in avoiding surface oxidation or contamination prior to the material growth, ensuring a high-quality film of the growth material on the prepared substrate surface. The passivation step can be performed using various techniques, such as chemical passivation, plasma
20 passivation, or thermal passivation.

B7. Examples of surface preparation for epitaxial material growth

B7.1 The first example process relates to Figure 6 and 9:

25 The surface of Si is smoothened with the cyclic removal process, and then a GaN material is grown on top of this surface.

Process Steps:

1. Preclean: Before starting the cyclic process, it is preferred that the silicon
30 substrate is free of contaminants and native oxides. This can be achieved through a pre-clean step, often involving a brief exposure to a plasma or chemical treatment to remove impurities. Buffered oxide etch (BOE) 10:1 for the native oxide removal on Si surface is advantageous, and can be performed by immersing the substrate into a

buffered HF for 30 s, followed by 30 s of rinsing in deionized water and dry blow with N₂ for 15 s.

2. Initial gas exposure for modifying a top-most surface layer of the surface: In the cyclic removal process, first, the Si surface is exposed to chlorine gas, which chemisorbs on the surface. This step is self-limiting and slows down or stops as a function of time or, equivalently, as a function of species dosage. For faster chemisorption, it may be advantageous to activate Cl₂ gas with, e.g. plasma. Example process parameters for this step:

- Chlorine (Cl₂) Flow: Ranging from 1 to 40 sccm (standard cubic centimeters per minute).
- Pressure: between 1 mTorr (millitorr) and 60 mTorr, and set to 3 mTorr in a preferred example.
- Time: between 15 milliseconds to 2 minutes. For inactivated Cl₂ gas at room temperature, a preferred time is between 5 s and 60 s and is determined based on the process pressure. For 20 mTorr process pressure at room temperature, an optimal exposure time was determined to be 20 s. Specific optimal parameters may depend on other process details, such as the gas flow. The optimal gas flow is determined based on the process chamber volume and the exposed sample surface. In an example a Cl₂ gas flow above 20 sccm was determined to be optimal for the process results. It was determined that there is no spontaneous Si etching with Cl₂ gas at room temperature if the gas is not activated.

3. Purge - evacuating excessive chemical species: After the surface chlorine chemisorption, the reactor is purged with an inert gas (such as argon) to remove any excess chlorine gas from the chamber volume. Example process parameters for this step:

- Argon (Ar) Flow: between 3 and 80 sccm.
- Purge Time: between 15 ms and 120 seconds, and set to 40 seconds in a preferred example.
- Pressure: Maintained between 1 and 60 mTorr, and set to 3 mTorr in a preferred example.

4. Activating the top-most modified surface layer to form volatile products, in this example using a plasma pulse step. During this step, a plasma is generated using an inert gas (such as argon (Ar) gas). Ions from the plasma are used to remove the

topmost activated layer by the chlorine chemisorption. Example process parameters for this step:

- Argon (Ar) Flow: Controlled from 1 to 40 sccm, and set to 20 sccm in a preferred example.
- 5 • Ion Energies: below 60 eV. Ion energies around 20 eV was determined to provide the best results.
- Time: between 3 seconds and 60 seconds, and set to 10 seconds in a preferred example.
- Pressure: between 1 mTorr and 60 mTorr, and set to 3 mTorr in a preferred
- 10 example.

5. Optional second purge step - removing etch products: Its primary purpose is to remove any remaining etchant gases, reaction byproducts, or other contaminants from the reaction chamber before proceeding with the next cycle of the cyclic removal process. Example process parameters for this step:

- 15 • Argon (Ar) Flow: Between 3 and 80 sccm. A flow at 20 sccm was determined to provide the best results.
- Purge Time: between 2 and 20 seconds. A purge time of 2 seconds was determined to provide the best results.
- Pressure: Maintained between 1 and 60 mTorr. A pressure at 3 mTorr was
- 20 determined to provide the best results.

6. Repeat Cycles:

- Steps 2 through 5 are repeated for a specific number of cycles. An advantageous number of repetitions was determined to be between 5 to 200 repetitions, and is determined based on the original roughness of the Si surface. For a typical Si surface
- 25 after a chemical-mechanical polishing (CMP) process, the optimal number of cycles was determined to be 20 cycles.

These precise parameters were particularly advantageous to smoothen the Si surface to the extent needed to grow improved GaN material on top of this surface, see Figure 10.

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B7.2. The second example process relates to Figure 8 and 9:

In this example, the process outlined in the first example is followed by a deposition process to overgrow impurities and defects on the surface. Particularly advantageous results are achieved when the deposition process is done in the same chamber as the

cyclic removal process presented in the first example. This allows minimizing the top surface oxidation after previous processing.

Process Steps:

- 5 B1. Purge: This step removes excess gases. Example process parameters for this step:
- Inert Gas Purge: Argon (Ar), set to 20 sccm in a preferred example.
 - Purge Time: between 30-60 s, set to 30 s in a preferred example.
 - Purge Pressure: between 1-10 mTorr. A pressure at 10 mTorr was determined
- 10 to provide the best results.
2. Deposition process - Gallium (Ga) Precursor pulse: Introduce a controlled pulse of trimethylgallium (TMG) into the reaction chamber. TMG reacts with the GaN surface to form a monolayer of gallium atoms. Example process parameters for this step:
- TMG Flow Rate: between 10-50 sccm, was set to 20 sccm in a preferred
- 15 example.
- Pulse Time: between 0.1-2 seconds, was set to 1 s in a preferred example.
 - Chamber Pressure: between 1-100 mTorr, was set to 50 mTorr in a preferred example.
 - TMG Vaporizer Temperature: between 60-100°C, was set to 80°C in a preferred
- 20 example.
3. Purge - Inert Gas: to remove excess TMG and reaction byproducts from the previous step, ensuring that only one monolayer of gallium atoms remains on the substrate surface. Example process parameters for this step:
- Ar Flow Rate: between 50-200 sccm, was set to 100 sccm in a preferred
- 25 example.
- Purge Time: between 10-30 seconds, was set to 20 s in a preferred example.
 - Purge Pressure: between 1-10 mTorr, was set to 10 mTorr in a preferred example.
- 30 4. Deposition process - Nitrogen (N) Precursor pulse: Ammonia (NH₃) is introduced to react with the exposed gallium atoms on the surface, forming a monolayer of GaN. This completes the deposition of one atomic layer of GaN. Example process parameters for this step:
- H₃ Flow Rate: between 10-50 sccm, was set to 20 sccm in a preferred example.

- Pulse Time: between 0.1-2 seconds, was set to 1 s in a preferred example.
 - ALD Chamber Pressure: between 1-100 mTorr. A pressure at 50 mTorr was determined to provide the best results.
5. Purge - Inert Gas: Similar to the previous purge step, argon gas is used to remove excess NH₃ and reaction byproducts to prepare the surface for the next cycle.
- Example process parameters for this step:
- Ar Flow Rate: between 50-200 sccm
 - Purge Time: between 10-30 seconds
 - Purge Pressure: between 1-10 mTorr
6. Repeat Cycles: Steps 2 through 5 are repeated for a specific number of cycles. An advantageous number of repetitions was determined to be between 5 to 200 repetitions. The optimal number of cycles was determined to be 20 cycles, to build up the initial nucleation layer of GaN.
- The process is preferably continuously monitored, and the process parameter data is analyzed. Such in situ characterization techniques as, for example, optical emission spectroscopy (OES) and optical reflectometry, can be used for this process monitoring. The preferred way for this process monitoring is by verifying the actual process parameters and comparing them to reference values. Specifically, it was found to be the best to monitor the process by in-line tracking radio frequency (RF) signal applied and reflected to maintain the plasma and the corresponding matching parameters for the RF line. This monitoring allows precise adjustment of the number of cycles needed to prepare the surface for subsequent GaN material growth on top. Depending on the process monitoring results, it may be advantageous to repeat the process steps outlined in the first example. In some cases, the plasma pulse step (step 3) needs to be adjusted, typically by increasing the ion energy by keeping it below 90 eV. Ion energy around 30 eV were in some examples determined to provide the best results. In some examples, the steps in of the above first and second examples may need to be repeated a number of times. A repetition of 5 times was determined to provide the optimal results. The number of these repetitions can be optimized and determined based on situ monitoring and process tracking.

B8. Experimental Results

This section provides a detailed description of the experimental results obtained using the disclosed method for preparing substrate surfaces for improved material growth. The results demonstrate the effectiveness of the method in reducing surface roughness and improving the quality of the grown material.

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B8.1. Atomic Force Microscopy (AFM) Micrographs

In one example, Atomic Force Microscopy (AFM) micrographs were used to analyze the surface roughness of the substrate before and after the cyclic removal process.

10 The AFM micrographs provide a visual representation of the surface topography, allowing for a direct comparison of the surface roughness before and after the process. The reduction in surface roughness observed in the AFM micrographs was also quantitatively analyzed to demonstrate the effectiveness of the method.

15 B8.1.1. Initial Si Surface and Surface after Cyclic Etching

In one example, the initial Si surface (Figure 10, left) was compared to the surface after a cyclic removal process, i.e. cyclic etching (Figure 10, right). The AFM micrographs show a significant reduction in surface roughness after the cyclic removal process. The top parts of the micrographs, 2500 and 2504, display a scan area of 1 μm^2 . The bottom graphs 2501, 2502, 2503, 2505, 2506, and 2507 are line scans in different places of the corresponding scan areas 2500 and 2504: top, middle, and bottom, respectively. The reduction in surface roughness after the cyclic removal process demonstrates the effectiveness of the method in preparing the substrate surface for improved material growth.

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B8.1.2. Initial GaN Surface and Surface after Cyclic Deposition and Etching

In another example, the initial GaN surface (Figure 11, left) was compared to the surface after cyclic deposition followed by a cyclic removal process, i.e. cyclic etching (Figure 11, right). The AFM micrographs show a substantial reduction in surface roughness after the combined cyclic deposition and removal process. This result demonstrates that the optional deposition process may further enhance the surface preparation for improved material growth.

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The reduction in surface roughness observed in these examples demonstrates the advantages of the disclosed method in preparing substrate surfaces for improved material growth. By reducing surface roughness, the method may significantly reduce the number of defects in the material grown on the surface, resulting in higher-quality films. Additionally, the method may be combined with ion beam shaping processes to further enhance the surface preparation and improve material growth on various substrates.

The terminology used herein is for the purpose of describing particular aspects only and is not intended to be limiting of the disclosure. As used herein, the singular forms "a," "an," and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items. It will be further understood that the terms "comprises," "comprising," "includes," and/or "including" when used herein specify the presence of stated features, integers, actions, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, actions, steps, operations, elements, components, and/or groups thereof.

20

It will be understood that, although the terms first, second, etc., may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first element could be termed a second element, and, similarly, a second element could be termed a first element without departing from the scope of the present disclosure.

25

Relative terms such as "below" or "above" or "upper" or "lower" or "horizontal" or "vertical" may be used herein to describe a relationship of one element to another element as illustrated in the Figures. It will be understood that these terms and those discussed above are intended to encompass different orientations of the device in addition to the orientation depicted in the Figures. It will be understood that when an element is referred to as being "connected" or "coupled" to another element, it can be directly connected or coupled to the other element, or intervening elements may be

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present. In contrast, when an element is referred to as being "directly connected" or "directly coupled" to another element, there are no intervening elements present.

5 Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs. It will be further understood that terms used herein should be interpreted as having a meaning consistent with their meaning in the context of this specification and the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

10

It is to be understood that the present disclosure is not limited to the aspects described above and illustrated in the drawings; rather, the skilled person will recognize that many changes and modifications may be made within the scope of the present disclosure and appended claims. In the drawings and specification, there have been
15 disclosed aspects for purposes of illustration only and not for purposes of limitation, the scope of the disclosure being set forth in the following claims.

Claims

1. A method for surface conditioning based on cyclic processing comprising:
 - activating a surface;
 - removing excess materials from the surface and surrounding environment;
 - applying a low-energy particle treatment to the surface; and
 - repeating the above steps until the surface has a desired smoothness.
2. The method according to claim 1, wherein the low-energy particle treatment uses ions.
3. The method according to claim 2, wherein the low-energy particle treatment is atomic layer etching (ALE).
4. The method according to claim 3, wherein the low-energy particle treatment is atomic layer etching (ALE) with molecular activation.
5. The method according to claim 1, wherein the cyclic processing comprises deposition steps.
6. The method according to claim 5, wherein the deposition steps result in an atomic layer deposition (ALD).
7. The method according to any one of claims 2 to 6, comprising a combination of etching and deposition.
8. The method according to any one of claims 2 to 7, comprising alternating etching and deposition.
9. The method according to any one of claims 1 to 8, wherein the repeating of the steps is performed until the process has no further effect on different processed surfaces.
10. The method according to any one of claims 1 to 9, further comprising ion beam shaping technology.

11. The method according to claim 10, further comprising angled particle beam etching.
12. The method according to any one of claims 1 to 11, wherein the surface is a side wall surface.
13. The method according to any one of claims 1 to 12, wherein the surface is an inclined surface.
14. The method according to any one of claims 1 to 13, wherein the surface is selected from the group consisting of semiconductor surfaces, metal surfaces, dielectric surfaces, and 2D material surfaces.
15. The method according to any one of claims 1 to 14, wherein the surface is a patterned surface.
16. The method according to any one of claims 1 to 15, wherein the surface is a non-patterned surface.
17. The method according to any one of claims 1 to 16, wherein the activation of the surface comprises applying a gas exposure to the surface.
18. The method according to any one of claims 1 to 17, wherein the activation of the surface comprises exposing the surface to a chemical solution.
19. The method according to any one of claims 1 to 18, wherein the activation of the surface comprises heating the surface to a specific temperature.
20. The method according to any one of claims 1 to 19, wherein the activation of the surface comprises applying a particle beam to the surface.

21. The method according to any preceding claim, wherein the low-energy particle treatment comprises a low-energy particle beam with a particle energy between 10 eV and 100 eV.

22. The method according to any one of claims 1 to 20, wherein the low-energy particle treatment comprises a low-energy plasma treatment with a plasma power between 1 W and 50 W.

23. A surface conditioned by the method according to any one of claims 1 to 22.

24. A method of preparing a surface of a substrate and epitaxial material growth, the method comprising the steps of:

exposing the surface to a cyclic removal process to remove impurities and defects from the surface comprising:

modifying a top-most surface layer of the surface by introducing a chemical species, such as halogens, in a process chamber volume enclosing the substrate, to obtain a top-most modified surface layer of the surface,

evacuating excessive chemical species from the process chamber volume,

activating the top-most modified surface layer to form volatile products,

optionally removing etch products from the process chamber volume,

wherein the cyclic removal process is followed by epitaxial material growth, and

wherein the growth material is different from the material of the surface.

25. Method according to claim 24, wherein the modifying of the top-most surface layer is done in a gas phase that contains only neutral species.

26. Method according to any of the previous claims 24 - 25, wherein the cyclic removal process has an etch rate per cycle thereof, wherein the etch rate approaches zero as the number of cycles increases.

27. Method according to any of the previous claims 24 - 26, wherein the activation of the top-most modified surface layer is done in a gas phase that does not involve surface bombardment with ions.

28. Method according to any of the previous claims 24 – 27, comprising a step of a deposition process to overgrow impurities and defects on the surface comprising modifying the top-most surface layer by introducing a chemical species in the process chamber volume for said overgrow.

29. Method according to claim 28, wherein the chemical species for said overgrow comprises gallium, nitrogen, and optionally aluminum.

30. Method according to claim 28 or 29, where the deposition process is cyclic.

31. The method, according to any of the previous claims 28 – 30, wherein the deposition process has a deposition rate per cycle thereof, wherein the deposition rate approaches zero as the number of cycles increases.

32. Method according to any of the previous claims 24 – 31, wherein at least one of the steps includes a self-limiting reaction that slows down or stops as a function of time or, equivalently, as a function of species dosage.

33. Method according to claim 32, wherein the self-limiting reaction comprises chemisorption, deposition, extraction, and/or conversion such as oxidation or nitridation.

34. Method according to any of the previous claims 24 - 33, comprising an additional passivation step preceding the epitaxial material growth to avoid surface oxidation or contamination prior to the material growth.

35. Method according to any of the previous claims 24 - 34, wherein the surface comprises a pattern, such as regularly arranged holes, lines, and/or pillars.

36. Method according to any of the previous claims 24 – 35, comprising retrieving process control information, such as information from optical emission and residual gas analysis, wherein process parameters of the method are adjusted based on the process control information.

37. A method for epitaxial material growth on a surface of a substrate, comprising a cyclic process comprising a sequence of

any of the steps according to any of claims 24 – 27 followed by any of the steps according to any of claims 28 – 34, the method comprising

repeating the sequence a plurality of times,
epitaxial material growth of a growth material on the surface, and
wherein the growth material is different from the material of the surface.

38. The method, according to claim 37, where the steps are repeated until at least one of said steps has no further effect on the surface.