

Relaxation and Transfer of Strained Material Layers

Field of Invention

The present invention relates to the field of compliant substrates employed in the manufacture of semiconductor devices and, in particular, to the relaxation of strained material islands and the transfer of the at least partially relaxed strained material islands to some support substrate that can suitably be used for further semiconductor manufacture processes.

Background of the invention

The growth of thin films on substrates by heteroepitaxy is an important manufacturing step in the semiconductor technology. For instance, in the field of light-emitting semiconductor devices or solar cells there is a need to grow heteroepitaxial films on substrates as sapphire or SiC to form a final semiconductor device. After transfer of the heteroepitaxial films to another substrate these films can, for instance, be used for epitaxial growth of layers used in electronic and opto-electronic applications.

However, when films are formed by heteroepitaxy on substrates with different lattice constants and different coefficients of thermal expansion as compared to the ones of the films detrimental effects on material quality of layers grown on the films are caused by compressive/tensile strain and the corresponding generation of defects like dislocations, cracks, plastic relaxation etc. that result in detrimental effects on the material quality of layers grown thereon.

Thus, in the art, compliant layers, e.g., low-viscosity layers, have been provided between the heteroepitaxial film and a target substrate in order to release the strains by heat treatment.

Presently used methods for the relaxation of strained heteroepitaxial films, however, often not show satisfying results with respect to the suppression of buckling, etc. Moreover, the transfer of heteroepitaxial films grown on a seed (growth) substrate including some seed layer to another substrate that is to be used for the further manufacture of a particular semiconductor raises the problem of maintaining the heteroepitaxial films intact, in general, and, in particular, removing the seed substrate without damaging the heteroepitaxial films.

Embodiments of the present invention seek to provide a method for the formation of reliably relaxed and intact material layers (islands) that can suitably be used for the manufacture of a semiconductor device.

Description of the Invention

According to a first aspect of the present invention, there is provided a method for the formation of an at least partially relaxed strained material layer, the method comprising the steps of

providing a seed substrate;

patterning the seed substrate;

growing a strained material layer on the patterned seed substrate;

transferring the strained material layer from the patterned seed substrate to an intermediate substrate; and

at least partially relaxing the strained material layer by a heat treatment.

The expression "strained material layer" alternatively denotes a continuous or a discontinuous layer exhibiting islands. The seed substrate may be a massive uniform substrate or a hybrid substrate comprising a seed layer bonded to or grown on some support substrate. In the process of transferring the strained material layer from the patterned seed substrate to the intermediate substrate the seed substrate may be removed by one or more of etching, mechanical polishing, grinding, electromagnetic or laser irradiation, etc. Residual material of the seed substrate that possibly remains atop of the strained material layer after the transfer can be removed by polishing or etching.

The expression "patterning" is used in a very general sense comprising a) structuring a surface of the seed substrate, e.g., by etching, in particular, plasma or chemical etching, or scribing irradiation and forming islands and recesses, and b) depositing a patterned mask on a surface of the seed substrate substantially without removing any material of the seed substrate.

Particularly, according to one embodiment it is provided a method for the formation of at least partially relaxed strained material islands comprising

providing a seed substrate;

patterning the seed substrate to form seed substrate islands;

growing a strained material layer on the patterned seed substrate, in particular, on the seed substrate islands;

transferring the strained material layer from the patterned seed substrate to an intermediate substrate;

forming islands of the strained material layer; and

at least partially relaxing the strained material islands by a heat treatment.

The formation of the islands of the strained material may be directly achieved by epitaxially growing the strained material layer following the shape of the surface of the seed substrate islands and stopping the growth before coalescence of the grown strained material islands or by forming islands from a relatively plane surface of strained material obtained by epitaxially growing the strained material layer first following the shape of the surface of the seed substrate islands and then forming a plane surface by coalescence of the formed strained material islands.

It should be noted that, in general, the step of forming islands of the strained material layer can be performed either before the transfer from the patterned seed substrate to an intermediate substrate or after this transfer.

Alternatively, a patterned mask comprising closed and open regions (covering and exposing a surface of the seed substrate, respectively) is deposited on the seed substrate and strained material islands are grown on the seed substrate in the open regions of the mask (exposed regions of the surface of the seed substrate). The grown strained material islands are subsequently transferred to an intermediate substrate and after the transfer they are subject to heat treatment in order to at least partially relax the strained material islands on the intermediate substrate.

The strained material islands formed by means of the patterned seed substrate may have any desired shape, e.g., rectangular stripe-like or circular, and they may have dimensions of about 100 x 100 micrometers to some square millimeters. Individual strained material islands may be spaced at some 10 micrometers to about 100 micrometers from each other. The depth of the recesses (trenches) in the seed substrate separating the strained material islands may range from a few nanometers to some tens of micrometers. The size of the islands and trenches may be adapted according to thermomechanical strain in the material.

By the method according to one of the above-described examples it is possible to directly obtain strained material islands on a patterned seed substrate by epitaxially growing the strained material on a surface of the seed substrate. In particular,

the method can provide the advantage that the crystalline quality of the grown strained material may be significantly higher than in the art wherein epitaxial growth on a continuous surface of a seed layer is performed. In particular, cracks may be avoided. Since the difference of coefficients of thermal expansion between the strained material islands and seed substrate has a less significant impact on the crystalline quality and, thus, cracks are particularly avoided in the grown material. In other words, compared to conventionally manufactured strained material layers, in embodiments of the present invention, it is possible to use a seed substrate with a higher difference of coefficients of thermal expansion with respect to the chosen strained material, e.g., GaN or InGaN, and still to get the same desired crystalline quality.

Since it is possible to use more mismatched seed substrates low cost substrates can be employed which was not allowable in the art. These low cost substrates can be removed and disposed without any need for re-cycling. For example, silicon seed substrates can be used to grow III/V materials such as GaN and InGaN by epitaxy. Epitaxy of GaN and InGaN on silicon seed substrates can be performed with no detrimental effects if the silicon seed substrate is patterned before epitaxial growth.

Moreover, as the strain level may be lower in epitaxial material by using a patterned seed substrate, it is possible to use a seed substrate with a larger lattice mismatch and get the same crystalline quality than in conventional process.

In addition, as the strain level may be lower with a patterned seed substrate it may allow for a higher thickness of the resulting strained material islands as compared to the same seed substrate of plane surface with no cracks.

In this context, it should also be noted that some buffer layer as known in the art may be provided between the seed substrate and the strained material in order to further increase the crystalline quality in the strained material. The buffer layer may show islands due to the islands of the patterned seed substrate or may be a continuous layer if formed until islands of the buffer layer material corresponding to the islands of the seed substrate undergo coalescence.

For example, a GaN buffer is preferably deposited on a silicon patterned seed substrate before epitaxy of InGaN material. As cracks may be avoided in the GaN buffer layer, the quality of InGaN may be less damaged than by using a conventional method. Furthermore, the lattice mismatch strain may also be less significant in the GaN buffer such that the strain in InGaN material may also be less significant. This may allow a higher layer thickness or to use higher Indium content in the InGaN layer as compared to the art.

According to one example, preferably, the strained material island growth is stopped before the onset of island coalescence, that is islands may be kept apart from the others.

Alternatively, it is also conceivable to grow a strained layer on a seed substrate with islands (the top of the strained material layer has islands) having a size small enough to allow coalescence of the strained material. The size of pattern depends on the growth conditions and material but the scale of the seed islands is usually on the order of nanometers. In this case, dislocations in the strained layer may be annihilated to lead to smaller dislocation density along with reducing defects and crack. The method for forming Islands of strained material is the same as used to pattern the seed substrate. It can be performed before or after transfer of the strained layer onto an intermediate substrate for the relaxation process.

In case of the use of a buffer layer, it is advantageous that the buffer layer is grown on the pattern seed substrate up to coalescence of the layer. The strained material that is to be relaxed is then deposited on the continuous buffer layer. The low dislocation density in the buffer layer may avoid damaging the strained material at the dislocation sites.

For the process of the transfer of the strained material layer (islands) to the intermediate substrate the seed substrate must preferably be detached from the strained material. This detachment can be facilitated by implanting ions in the seed substrate below the strained material layer to form a weakened layer and detaching the strained material layer from the seed substrate at the weakened layer by heat treatment.

Alternatively, ions can be implanted in the strained material layer to form a weakened layer and the strained material layer can be detached from the seed substrate at the weakened layer by heat treatment. In particular, detachment of the strained material layer without residual seed substrate material is thereby made possible. It goes without saying that the thermal budget of the heating treatment performed for the detachment of the seed substrate is different from the one performed for the relaxation of the strained material.

In the above examples, the step of transferring the strained material layer from the seed substrate to the intermediate substrate may comprise depositing a low-viscosity layer, in particular, a buried compliant layer, on the strained material layer and bonding the low-viscosity layer to the intermediate substrate.

The low-viscosity layer may comprise or consists of borophosphosilicate glass, BPSG, or an SiO_2 - compound comprising boron or phosphorous. A similar layer may be deposited on the intermediate substrate before bonding it to the strained material layer (islands) for the transfer process. The heat treatment for relaxation of the strained material transferred to the intermediate substrate then allows for some reflow of the low-viscosity material layer thereby resulting in at least partial relaxation of the strained material. By the expression "low-viscosity" reflow properties at the heat treatment are particularly denoted. The process of forming strained material islands may comprise patterning the deposited low-viscosity layer accordingly (see detailed description below). Borophosphosilicate glass exhibits desired reflow characteristics at temperatures of about 800 or 850 °C depending of the actual composition of the glass thereby allowing relaxation of the strained material such as InGaN.

The partially relaxed strained material islands can be transferred to a target substrate. For this, a high-viscosity layer, e.g., a buried layer comprising or consisting of an oxide (thermal oxide material), may be formed on the at least partially relaxed strained material islands and bonded with the target substrate. The term "high-viscosity" refers to a glass transition temperature higher than the one of the "low-viscosity" material. For example, a low-viscosity BPSG layer that includes 4.5 % of boron and 2 % of phos-

phorous exhibits desired reflow characteristics at temperatures of about 800°C. Most of low viscosity oxide materials have a glass transition temperature around 600-700°C, On the other hand, the glass transition temperature of the high-viscosity oxide material is above 1000°C and preferably above 1200°C. The target substrate may be of the same material as the seed substrate or the intermediate substrate, for example.

When the strained material is polar, as for the c-plane III/N material, and when the process is performed by growing the strained material on a seed substance followed by a two-step transfer process from the seed substance to the intermediate substance and from the intermediate substance to the target substance, the polarity of the face of the relaxed strained material opposing the face of growth on the seed substance that is suitable for any subsequent epitaxial growth of layers can be maintained. In particular for III/N material, if the exposed face exhibits a III-element polarity after the growth on the seed substance, the exposed face after the two-step transfer process will also exhibit a III-element polarity that is the most suitable for a subsequent epitaxial growth of a III/N layer. If the exposed face after the growth is an N-face, a one-step transfer process may be enough to allow the subsequent epitaxy on the right polarity.

When the initial-strained material is non polar, the two-step transfer process may be avoided and an epitaxial growth may occur on the at least partially relaxed material bonded to the intermediated substrate. In this case, the low viscosity layer may preferably be chosen to remain stable with no reflow at the temperature of the epitaxy.

According to a second aspect of the present invention, there is provided a method for the manufacture of a semiconductor device, comprising providing at least partially relaxed strained material on a target substrate according to one of the above-described examples as described with respect to the first aspect, and further comprising epitaxially growing at least one material layer on the formed at least partially relaxed strained material, in particular, layers for LED or photovoltaic or laser device layers.

According to a third aspect of the present invention, there is provided

a wafer comprising:

a support structure, in particular, consisting of sapphire or silicon;

a high-viscosity layer,

islands of at least partially relaxed strained material obtained by the method according to one of the above-described examples, in particular, with an area size from 100 micrometers x 100 micrometers to 1 mm x 1 mm; and of a thickness of more than 500 Angstroms.

The wafer may comprise at least one active layer on the relaxed strained material layer/islands, in particular LED, laser or photovoltaic device layers.

Additional features and advantages of the present invention will be described with reference to the drawings. In the description, reference is made to the accompanying figures that are meant to illustrate preferred embodiments of the invention. It is understood that such embodiments do not represent the full scope of the invention.

Figure 1 illustrates an example of the inventive method comprising the steps of patterning a seed substrate by etching and growing a strained material layer on the patterned seed substrate.

Figure 2 illustrates another example of the inventive method comprising the steps of depositing a mask on the seed substrate comprising open regions and growing strained material islands on the seed substrate in the regions not covered by the mask.

Figure 3 illustrates another example of the inventive method wherein a strained material layer is grown on a buffer layer formed with a plane surface on a patterned seed substrate.

In the following, two alternative embodiments of the herein disclosed method for the formation of at least partially relaxed strained material layers are described with reference to Figures 1 and 2. As shown in Figure 1, a seed substrate 1 is provided for the growth of a strained material layer. The seed substrate 1 may, e.g., be a sapphire substrate or a silicon substrate. The seed substrate 1 is patterned by etching to obtain seed substrate islands 1' separated by recesses. The seed substrate islands may, e.g., be sized to 1 x 1 millimeters and space apart at about 10 to 1000 micrometers. The recesses may have a depth of about 1 micrometer.

After patterning of the seed substrate 1 epitaxy of a strained material, e.g., InGaN with 10 % Indium is performed up to a thickness of the strained material layer 2 of about 250 nanometers. In order to improve the crystalline quality of the strained material layer 2 a buffer layer (not shown) may be deposited on the patterned seed substrate, in particular, the seed substrate islands 1', before growth of the strained material layer 2. The buffer layer may comprise an AlN nucleation layer of 50-100 nm thick deposited on the silicon surface and below a GaN layer of few micrometers thick. The growth of the buffer layer is stopped before coalescence of the material.

A low-viscosity (compliant) layer 3 is deposited on the strained material layer 2, in particular, above the seed substrate islands 1'. The thickness of the low-viscosity layer 3 may be about 500 nanometers.

A low-viscosity layer similar to the low-viscosity layer 3 is deposited on an intermediate substrate 4 to which the strained material layer 2 shall be transferred. The intermediate substrate 4 may be of the same material as the seed substrate 1, for example, made of silicon. The low-viscosity layer deposited on the intermediate substrate 4 may have a thickness of about 1 micrometer, for example. Then, both the low-viscosity layer 3 deposited on the strained material layer 2 and the low-viscosity layer deposited on the intermediate substrate 4 are polished. After this polishing step that may result in a thickness of the low-viscosity material of about 1 micrometer the strained material layer 2 is bonded via the low-viscosity layers to the intermediate substrate 4.

After the bonding step the seed substrate 1 is removed, e.g., by plasma or chemical etching and/or grinding. Moreover, after removal of the seed substrate 1 low-viscosity material islands 3' may be obtained by etching. Alternatively, the low-viscosity layer 3 deposited on the strained material layer 2 is etched before the bonding/transfer to the intermediate substrate 4. In this case, after the transfer the low-viscosity material that was deposited on the intermediate substrate 4 before the bonding step is etched in the spaces between the strained material islands 2' to obtain the low-viscosity material islands 3' shown in Figure 1.

Figure 2 shows an alternative example of a method for obtaining the strained material islands 2' and low-viscosity material islands 3' on the intermediate substrate 4. As shown in Figure 2, a seed substrate 1 (e.g., made of silicon or sapphire) is provided and partially covered by a mask layer 5. The mask layer 5 comprises open regions and may comprise SiO_2 or SiN material. In the open regions strained material 2 (e.g., GaN or InGaN with an Indium content of about 10 %) is grown up to a thickness of 500 nm and a low-viscosity layer 3 is deposited on the strained material 2 and the mask. Bonding of the low-viscosity layer 3 and a low-viscosity layer deposited on an intermediate substrate 4 and subsequent removal of the seed substrate 1 results in a transfer of the strained material islands 2' to the intermediate substrate 4. Low-viscosity material islands 3' are etched down to the intermediate substrate in the spaces between strained material islands 2', if this is needed to improve the subsequent relaxation step.

It should be noted that in both examples shown in Figures 1 and 2, alternatively, the strained material islands 2' may be provided on a continuous low-viscosity material layer on the intermediate substrate 4 (i.e., in particular, no etching of the low-viscosity layer deposited on an intermediate substrate 4 is performed).

The structures shown at the bottom of Figures 1 and 2 comprising the strained material islands 2' atop of the low-viscosity material islands 3' are subject to heat treatment, e.g., at some 800 or 850 °C over about 4 hours, in order to obtain at least partially relaxed strained material islands 2', e.g., partially relaxed InGaN islands with 10 % Indium, by reflow/plastic deformation of the low-viscosity material islands 3', e.g.,

borophosphosilicate glass, BPSG, or an SiO_2 - compound comprising boron or phosphorous.

Subsequently, a bonding layer can be deposited on the at least partially relaxed strained material islands 2' and/or on a target substrate. After bonding of the at least partially relaxed strained material islands 2' to the target substrate via the bonding layer(s) the intermediate substrate 4 and the low-viscosity material islands 3' can be removed, e.g., by etching or electromagnetic irradiation, to recover the surface of the at least partially relaxed strained material islands 2', e.g., InGaN islands. The at least partially relaxed strained material islands 2' can subsequently be used for the epitaxial growth of a structured material layer and, in particular, for epitaxial or homoepitaxial growth of a crystalline layer, that is to be employed in the manufacture of a particular semiconductor device useful in electronic, photovoltaic or opto-electronic applications such as LEDs or lasers.

In Figure 3 another example of the inventive method is shown wherein a strained material layer 2 is grown on a buffer layer 7 formed with a plane surface on a patterned seed substrate 1'. According to the example shown in Figure 3, an AlN nucleation layer 6 is formed on a patterned seed substrate 1'. Subsequently, a buffer layer 7, e.g., comprising GaN, is deposited above the AlN nucleation layer 6. During the deposition, first, the buffer layer 7 adapts to the shape of the islands of the patterned seed substrate 1'. However, according to the shown example the buffer layer 7 is deposited until the islands-like surface shape is leveled (coalescence of the islands of the buffer layer 7) such that a plane upper surface of the buffer layer 7 is formed.

Atop the plan surface of the buffer layer 7 strained material 2 is epitaxially grown and a borophosphosilicate glass layer is deposited 8 atop the grown strained material layer 2. Subsequently, the borophosphosilicate glass layer 8 and the strained material layer 2 are patterned to obtain strained material islands 2' and borophosphosilicate glass islands 8'. After this patterning process transfer to an intermediate substrate 4 by means of borophosphosilicate glass layer islands 3' formed on the intermediate substrate 4 is performed. It should be noted that the patterning of the borophosphosilicate glass layer 8 and the strained material layer 2 can also be performed after the

transfer to the intermediate substrate 4. After the transfer of the strained material islands 2' relaxation can be carried out as described above.

All previously discussed embodiments are not intended as limitations but serve as examples illustrating features and advantages of the invention. It is to be understood that some or all of the above described features can also be combined in different ways.

Claims

1. Method for the formation of an at least partially relaxed strained material layer, the method comprising the steps of

providing a seed substrate;

patterning the seed substrate;

growing a strained material layer on the patterned seed substrate;

transferring the strained material layer from the patterned seed substrate to an intermediate substrate; and

at least partially relaxing the strained material layer by a heat treatment.
2. The method according to claim 1, wherein

seed substrate islands are formed by the patterning of the seed substrate;

the strained material layer is grown on the seed substrate islands;

and further comprising

forming islands of the strained material layer, and wherein

the strained material islands are at least partially relaxed by the heat treatment.
3. The method according to claim 1, wherein

the patterning of the seed substrate comprises depositing a mask comprising open regions on a surface of the seed substrate;

strained material islands are grown on the surface of the seed substrate in the open regions of the mask on the seed substrate;

the strained material islands are transferred from the patterned seed substrate to the intermediate substrate; and

the strained material islands are at least partially relaxed by the heat treatment.

4. The method according to one of the preceding claims, wherein the step of transferring the strained material layer from the patterned seed substrate to the intermediate substrate further comprises

implanting ions in the patterned seed substrate below the strained material layer to form a weakened layer; and

detaching the strained material layer from the patterned seed substrate at the weakened layer by heat treatment.

5. The method according to one of the preceding claims, wherein the step of transferring the strained material layer from the patterned seed substrate to the intermediate substrate further comprises

implanting ions in the strained material layer to form a weakened layer; and

detaching the strained material layer from the patterned seed substrate at the weakened layer by heat treatment.

6. The method according to claim 1 to 3, wherein the step of transferring the strained material layer from the patterned seed substrate to the intermediate substrate comprises a removing step of the patterned seed substrate, wherein, in particular, the removing step comprises electromagnetic irradiation, grinding, mechanical polishing or etching of the patterned seed substrate.

7. The method according to claim 1 or 2, wherein at least one buffer layer is grown before the growth of the strained material layer on the patterned seed substrate.
8. Method according to one of the preceding claims, wherein the step of transferring the strained material layer from the patterned seed substrate to the intermediate substrate comprises depositing a low-viscosity layer, in particular, a buried compliant layer, on the strained material layer and bonding the low-viscosity layer to the intermediate substrate.
9. Method according to claim 8, wherein the low-viscosity layer comprises or consists of borophosphosilicate glass, BPSG, or an SiO_2 - compound comprising boron or phosphorous.
10. Method according to one of the preceding claims, further comprising the step of transferring the at least partially relaxed strained material layer to a target substrate.
11. Method according to claim 10, wherein the seed substrate, the intermediate substrate and the target substrate comprise or consist of sapphire or silicon.
12. Method according to one of the preceding claims, wherein the strained material layer consists of or comprises InGaN or GaN.
13. The method according to claim 12, wherein the strained material layer is an InGaN layer comprising at least 3 % In, in particular, at least 10 %.
14. The method according to one of claim 10 or 11 wherein the transferring of the at least partially relaxed strained material layer to the target substrate comprises the removing of the intermediate substrate in particular by etching, mechanical polishing grinding of the intermediate substrate or by electromagnetic irradiation.

15. Method according to claim 14, wherein the step of transferring the at least partially relaxed strained material islands to the target substrate comprises depositing a high-viscosity layer, in particular, a buried layer, on the at least partially relaxed strained material islands and bonding the high-viscosity layer to the target substrate.
16. Method for the manufacture of a semiconductor device, comprising providing at least partially relaxed strained material on a target substrate according to claim 15, and further comprising epitaxially growing at least one material layer on the formed at least partially relaxed strained material, in particular, layers for LED or photovoltaic or laser device layers.
17. A wafer comprising:
 - a support structure, in particular, consisting of sapphire or silicon;
 - a high-viscosity layer,
 - islands of at least partially relaxed strained material obtained by the method according to one of the preceding claims, in particular, with an area size from 100 micrometers x 100 micrometers to 1 mm x 1 mm; and of a thickness of more than 500 Angstroms.
18. A wafer according claim 17 further comprising at least one active layer on the relaxed strained material, in particular LED, laser or photovoltaic device layers.