SUBSTRATE FOR GROWING A III-V NITRIDE EPILAYER AND METHOD FOR SELECTING THE SAME

by Inventors

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Background of the Invention

1. Field of the Invention

The present invention relates generally to heteroepitaxial growth. More particularly, the present invention relates to substrates for growing III-V nitride epilayers and a method for selecting the same.

2. Description of the Related Art

III-V nitride semiconductors such as aluminium nitride (AlN), gallium nitride (GaN) and indium nitride (InN), and their alloys have desirable properties such as a wide band gap, thermal stability, and good thermal conductivity. These properties, either singularly or in combination, make possible the development of numerous semiconductor devices with remarkable applications that were previously technically impossible. Examples of such semiconductor devices and their applications include blue laser digital video discs (DVDs) with five times the recording capacity of red laser DVDs, aerospace components operable over a wide range of temperatures and which remain unaffected by radiation, and also miniaturized, high-power wireless transmitters.

Although possessing great potential and generating much research interest, commercial application of such semiconductor devices is impeded by a lack of suitable substrates on which to grow thin epitaxial films of III-V nitride semiconductors, also known as III-V nitride epilayers.

Sapphire, one of the most widely used substrates for the growth of III-V nitride epilayers, is of a different lattice constant than the III-V nitride epilayer. Consequently, the interface between the sapphire substrate and the III-V nitride epilayer experiences a reported lattice mismatch of 13.8%, resulting in a strain in the heterostructure formed.

Misfit dislocations are generated to accommodate the strain in the heterostructure. These misfit dislocations degrade the optical and electrical properties of the resultant semiconductor device. The significant lattice mismatch between the sapphire substrate and the III-V nitride epilayer produces a semiconductor device with a high dislocation density that degrades the performance of the device.

Differing coefficients of thermal expansion between the sapphire substrate and the III-V nitride epilayer also contribute to the strain experienced by the heterostructure.

Additionally, the difference in the coefficients of thermal expansion generates stresses in the heterostructure whenever there is a substantial change in processing temperature. These stresses may cause cracks in the heterostructure.

Apart from sapphire, zinc oxide (ZnO), silicon (Si) and gallium arsenide (GaAs) are also used as substrates for the growth of III-V nitride epilayers.

Because ZnO crystals sublime at very low temperatures, a ZnO substrate may disintegrate while a III-V nitride epilayer is being deposited, a process that typically occurs around 600°C to 750°C. The poor thermal stability of ZnO limits the use of ZnO as a substrate for growing III-V nitride epilayers.

Si and GaAs substrates have a reported lattice mismatch of approximately 20.1% and 25.3%, respectively, with III-V nitride epilayers. As discussed previously, a large lattice mismatch between a substrate and an epilayer will degrade the performance of a semiconductor device produced with such a substrate.

Furthermore, GaAs has poor thermal stability. The decomposition rate of GaAs is known to increase rapidly at temperatures above 700°C, which limits the processing temperature for the growth of III-V nitride epilayers on GaAs substrates. Hence, maximum epitaxial growth rate may not be attained.

In recent years, a number of substrates for the growth of III-V nitride epilayers, such as $LiAlO_2$, $LiGaO_2$, $MgAlScO_4$ and $CrNbO_2$, have been proposed. However, the thermal properties such as the coefficients of thermal expansion and melting points of the proposed substrates are not well quantified. As such, there exists a possibility for thermal

mismatch between the substrate and epilayer, which discourages the practical application of these substrates. Practical applications of these substrates have thus been limited.

In view of the foregoing, it is desirable to have a semiconductor device with an acceptable level of lattice-mismatch between the substrate and the III-V nitride epilayer. It is also desirable to have a substrate for growing a III-V nitride epilayer with a similar coefficient of thermal expansion as the III-V nitride epilayer. It is further desirable to have a substrate for growing a III-V nitride epilayer that is stable at processing temperatures.

Summary of the Invention

The present invention fills these needs by providing a substrate for growing a III-V nitride epilayer and a method for selecting the same. It should be appreciated that the present invention can be implemented in numerous ways, including as a process, an apparatus, a system, a device or a method. Several inventive embodiments of the present invention are described below.

One embodiment of the present invention provides a method for selecting a substrate to grow a III-V nitride epilayer. The method begins by selecting a physical property and a set of existing substrates to analyse. Thereafter, the physical property of each of the set of existing substrates is determined and analysed to establish a criterion for selecting the substrate. The physical property of a potential substrate is then determined to ascertain whether the potential substrate satisfies the criterion for selecting the substrate.

The physical property is preferably a lattice mismatch and may be determined by measuring a first atomic distance and a second atomic distance at a substrate-III-V nitride epilayer interface. The first atomic distance is between a pair of atoms on a cleavage plane, while the second atomic distance is between a pair of atoms on the III-V nitride epilayer. The lattice mismatch is then calculated from the first atomic distance and the second atomic distance.

Preferably, the cleavage plane contains only a single type of atoms. In addition, the first atomic distance and the second atomic distance are preferably a smallest atomic distance measured on the cleavage plane and a smallest atomic distance measured on the III-V nitride epilayer, respectively.

In a preferred embodiment, a further physical property is selected to establish a further criterion for selecting the substrate. A further set of existing substrates may be selected for the analysis. The further physical property may be a coefficient of thermal expansion or a melting point.

In another embodiment of the invention, a semiconductor device is provided. The semiconductor device comprises a substrate having a perovskite structure and a III-V nitride epilayer provided on the substrate. The III-V nitride epilayer is preferably provided on a cleavage plane of the substrate with only a single type of atoms.

Preferably, the substrate has a lattice mismatch of less than 13.8% with the III-V nitride epilayer. More preferably, the lattice mismatch between the substrate and the III-V nitride epilayer is less than 6.96%, and most preferably less than 0.06%.

Preferably, a coefficient of thermal expansion of the substrate differs from a coefficient of thermal expansion of the III-V nitride epilayer by between about $\pm 1.9\times10^{-6}$ K^{-1}.

Preferably, the substrate has a melting point greater than a processing temperature of the semiconductor device.

Preferably, the substrate is one of a group consisting of $SeCoO_3$, $SeNiO_3$, $SeMnO_3$, $TeCoO_3$, $TeNiO_3$, $TeMnO_3$, $SeZnO_3$, $SeCuO_3$ and $SeMgO_3$. Additionally, the III-V nitride epilayer is preferably provided on a (010) cleavage plane of the substrate. The III-V nitride epilayer is preferably a GaN epilayer.

In yet another embodiment of the invention, a semiconductor device is provided. The semiconductor device comprises a substrate selected from a group consisting of $SeCoO_3$, $SeNiO_3$, $SeMnO_3$, $TeCoO_3$, $TeNiO_3$, $TeMnO_3$, $SeZnO_3$, $SeCuO_3$ and $SeMgO_3$ and a III-V nitride epilayer provided on the substrate.

In a further embodiment of the invention, a method for selecting a substrate to grow a III-V nitride epilayer is provided. The method begins by selecting a set of existing substrates previously used as substrates upon which to grow a III-V nitride epilayer to analyze. Thereafter, a lattice mismatch between each of the set of existing substrates and the III-V nitride epilayer is determined and analyzed to establish a range of acceptable lattice mismatches. A lattice mismatch between a potential substrate and the III-V nitride epilayer is then determined to determine whether it falls within the range of acceptable lattice mismatches. A difference between a coefficient of thermal expansion of each of the set of existing substrates and a coefficient of thermal expansion of the III-V

nitride epilayer is also determined and analyzed to establish a range of acceptable thermal expansion coefficient differences. A difference between a thermal expansion coefficient of the potential substrate and the III-V nitride epilayer is then determined to determine whether it falls within the range of acceptable thermal expansion coefficient differences. Additionally, a melting point of each of the set of existing substrates is determined and analyzed to establish a minimum acceptable melting point. A melting point of a potential substrate is then determined to determine whether it is greater than or equal to the minimum acceptable melting point.

Other aspects and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the invention.

Brief Description of the Drawings

The present invention will be readily understood by the following detailed description in conjunction with the accompanying drawings. To facilitate this description, like reference numerals designate like structural elements.

Figure 1a illustrates a crystal structure of $SeCoO_3$ in accordance with one embodiment of the present invention.

Figure 1b illustrates a crystal structure of $SeNiO_3$ in accordance with one embodiment of the present invention.

Figure 1c illustrates a crystal structure of $SeMnO_3$ in accordance with one embodiment of the present invention.

Figure 1d illustrates a crystal structure of $TeCoO_3$ in accordance with one embodiment of the present invention.

Figure 1e illustrates a crystal structure of $SeZnO_3$ in accordance with one embodiment of the present invention.

Figure 1f illustrates a crystal structure of $SeCuO_3$ in accordance with one embodiment of the present invention.

Figure 1g illustrates a crystal structure of $SeMgO_3$ in accordance with one embodiment of the present invention.

Figure 2 illustrates a method for selecting a substrate to grow a III-V nitride epilayer in accordance with another embodiment of the present invention.

Figure 3 illustrates a schematic cross section of a semiconductor device in accordance with yet another embodiment of the present invention.

Detailed Description of the Preferred Embodiments

A substrate for growing a III-V nitride epilayer and a method for selecting the same are provided. In the following description, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be understood, however, to one skilled in the art, that the present invention may be practiced without some or all of these specific details. In other instances, well known process operations have not been described in detail in order not to unnecessarily obscure the present invention.

The present invention is based on a detailed analysis of a set of existing substrates to ascertain suitable substrates for growing a III-V nitride epilayer. In particular, physical properties such as the crystal structure, atomic spacing, cleavage planes, coefficient of thermal expansion and melting point of the existing substrates were studied to establish criteria for selecting a substrate to grow the III-V nitride epilayer. It will be appreciated that references to existing substrates are in respect of known substrates which have either been used or proposed for use to manufacture a semiconductor device with the III-V nitride epilayer.

An analysis of existing substrates to select a substrate for growing a GaN epilayer is discussed in detail by way of example. The same methodology may be applied to select substrates for growing other III-V nitride epilayers.

A criterion for lattice mismatch is first established based on an analysis of the lattice mismatch of a set of existing substrates, which may be obtained directly from literature or indirectly based on reported lattice constants, as shown in Table 1.

TABLE 1

Substrate	Crystal Structure	Lattice Constant (Å)			Cleavage plane	Reported mismatch
Si	Diamond	5.4309			(111)	20.1 %
GaAs	Zinc Blende	5.653			(110)	25.3 %
GaP	Zinc Blende	5.451			(110)	20.7 %
MgO	Cubic	4.216			(111)	-6.5 %
MnO	Cubic	4.445			(100)	-1.4 %
CoO	Cubic	4.2667			(100)	-5.4 %

NiO	Cubic	4.168			(100)	-7.6 %
$MgAl_2O_4$	Spinel (cubic)	8.083			(111)	-10.3 %
ZnO	Wurzite	3.252		5.213	(001)	2.0 %
$LiGaO_2$	Orthogonal	5.406	5.012	6.379	(001)	-0.1 %
Al_2O_3	Hexagonal	4.758		12.99	C plane	-13.8 %

Alternatively, the lattice mismatch of the set of existing substrates may be calculated by measuring the atomic distances at a substrate-GaN epilayer interface, in particular, the atomic distance between atoms on a cleavage plane d_{sub} and the atomic distance between atoms on the GaN epilayer d_l, using a crystallographic viewer software such as Cerius[2], and using the measured atomic distances to calculate the lattice mismatch between the substrate and the GaN epilayer with the following equation:

$$Lattice\ \ mismatch = \frac{d_{sub} - d_l}{d_l} * 100\% \qquad (1)$$

The smallest measured atomic distance may be employed to calculate the lattice mismatch. In this instance, the smallest measured d_l at the substrate-GaN epilayer interface, that is, between Ga-Ga atoms, is 3.189 Å.

Applying this value of d_l to equation (1), the lattice mismatch at the substrate-GaN epilayer interface can be calculated. The measured d_{sub} for the set of existing substrates and the corresponding lattice mismatch are tabulated in Table 2.

TABLE 2

Substrate	Cleavage plane	Measured atomic distances, d_{sub}		Calculated mismatch
Si	111	Si-Si	3.84	20.41 %
GaAs	110	Ga-Ga	3.997	25.33 %
GaP	110	Ga-Ga	3.85	20.72 %
MgO	111	O-O	2.98	-6.55 %
MnO	100	O-O	3.1429	-1.44 %
CoO	100	O-O	3.015	-5.45 %
NiO	100	O-O	2.956	-7.3 %
$MgAl_2O_4$	111	O-O	2.864	-10.19 %
ZnO	001	O-O	3.27	2.54 %
$LiGaO_2$	001	O-O	3.125	-2.01 %
Al_2O_3	001	O-O	2.719	-14.74 %
SiC	001	Si-Si	3.0745	-3.59 %

To minimise lattice strain caused by a lack of uniformity in bond strength between the substrate and the GaN epilayer, the GaN epilayer is preferably grown on a cleavage plane of the substrate with only a single type of atoms. Accordingly, a cleavage plane with the same type of atoms is preferably selected for the measurement of d_{sub}. By minimising lattice strain, defect formation may be prevented which, in turn, reduces the dislocation density at the substrate-GaN epilayer interface.

As observed from Table 1 and Table 2, there is a good agreement between the calculated and reported lattice mismatch, indicating that crystallographic analysis is appropriate for evaluating lattice mismatch.

Based on an analysis of the lattice mismatch determined for each of the existing substrates, a substrate for growing a GaN epilayer should preferably have less than 13.8% lattice mismatch with the GaN epilayer, more preferably less than 6.96% lattice mismatch, and most preferably less than 0.06% lattice mismatch.

In this example, potential substrates having a perovskite structure were investigated. Potential cleavage planes on the perovskite structure such as (100), (001), (010) and (110) were studied and d_{sub} was measured for the calculation of lattice mismatch. $SeCoO_3$, $SeNiO_3$, $SeMnO_3$, $TeCoO_3$, $TeNiO_3$, $TeMnO_3$, $SeZnO_3$, $SeCuO_3$ and $SeMgO_3$ were found to satisfy the criterion for selection. The cleavage plane, measured atomic distance d_{sub} and calculated mismatch of each of these substrates are tabulated in Table 3.

TABLE 3

Substrate	Cleavage plane	Measured atomic distances, d_{sub}		Calculated mismatch
$SeCoO_3$	010	O-O	3.187	-0.06 %
$SeNiO_3$	010	O-O	3.134	-1.72 %
$SeMnO_3$	010	O-O	3.278	2.79 %
$TeCoO_3$	010	O-O	3.252	1.91 %
$TeNiO_3$	010	O-O	3.215	0.82 %
$TeMnO_3$	010	O-O	3.318	4.04 %
$SeZnO_3$	010	O-O	3.184	0.16 %
$SeCuO_3$	010	O-O	3.411	6.96 %
$SeMgO_3$	010	O-O	3.168	-0.66 %

Figures 1(a) to (g) illustrate crystal structures of $SeCoO_3$, $SeNiO_3$, $SeMnO_3$, $TeCoO_3$, $SeZnO_3$, $SeCuO_3$ and $SeMgO_3$, respectively, with the atomic distance between O-O atoms in the (010) cleavage plane indicated therein.

Apart from lattice mismatch, differences in the coefficients of thermal expansion between a III-V nitride epilayer and a substrate also degrade the performance of a resultant semiconductor device. Hence, a second criterion for selecting a substrate based on an analysis of the coefficients of thermal expansion for a second set of existing substrates is preferably established.

A list of the coefficients of thermal expansion, at room temperature, for a GaN epilayer and the second set of existing substrates, as well as the difference between the two, is provided in Table 4. These values were obtained from literature.

TABLE 4

Substrate	Coefficient of Thermal Expansion ($\times 10^{-6}$)	Difference in Coefficient of Thermal Expansion ($\times 10^{-6}$)
GaN	5.59	
Al_2O_3	7.49	1.90
$MgAl_2O_4$	7.49	1.90
MgO	12.8	7.21
SiC	4.19	-1.40
ZnO	2.89	-2.70
Si	3.59	-2.00
GaP	4.69	-0.90
GaAs	5.99	0.40
$LiGaO_2$	7.49	1.90

The difference in the coefficient of thermal expansion between the second set of existing substrates and the GaN epilayer is in the range of $\pm 1.9\times10^{-6}$ K^{-1}, which serves as the second criterion for the selection of a substrate.

The coefficients of thermal expansion for the potential substrates were predicted using a theoretical approach proposed by Inaba, et. al., in "*Semi-Empirical Estimation of Thermal Expansion Coefficients of Perovskite-Type Oxides*" (Journal of the Ceramic Society of Japan, 106 [3] 272-278, 1998) and are tabulated in Table 5.

TABLE 5

Substrate	Coefficient of Thermal Expansion ($\times 10^{-6}$)	Difference in Coefficient of Thermal Expansion ($\times 10^{-6}$)
GaN	5.59	
$SeCoO_3$	5.53	-0.06
$SeNiO_3$	5.58	-0.01
$SeMnO_3$	5.72	0.13
$TeCoO_3$	6.53	0.94
$TeNiO_3$	6.35	0.76
$TeMnO_3$	6.49	0.90
$SeZnO_3$	5.63	0.04
$SeCuO_3$	5.65	0.06
$SeMgO_3$	5.59	0.00

Table 5 shows that these substrates satisfy the second criterion for the selection of a new substrate. As the difference in coefficient of thermal expansion between the GaN epilayer and the potential substrates is very small, minimal thermal mismatch is expected from a GaN semiconductor device produced with one of these substrates.

Growth of the GaN epilayer typically occurs in the range of 600°C to 750°C. However, prior to growing the GaN epilayer on a substrate, the substrate is typically heated to around 800°C to 950°C. To avoid decomposition of the substrate during processing, a substrate should preferably be stable at the processing temperatures of a semiconductor device. This requirement serves as a basis for the establishment of a third criterion for the selection of the substrate.

Reported melting points for a third set of existing substrates were studied to determine an acceptable melting point for the substrate. A list of the reported melting points for the third set of existing substrates is provided in Table 6.

TABLE 6

Substrate	Melting point (°C)
Al_2O_3	2030
$MgAl_2O_4$	2130
NiO	1726
MgO	2800
CoO	1830
SiC	Sublimes
MnO	2800
ZnO	1975

Si	1414
GaP	1348
GaAs	1238
$LiGaO_2$	1600

Table 6 shows that the third set of existing substrates has melting points ranging from 1238°C to 2800°C. Therefore, a substrate with a melting point of greater than 1100°C may be acceptable for growing a GaN epilayer. This forms the third criterion for the selection of a substrate.

Melting points for the potential substrates are predicted using the Neural Network Model Builder (NNMB) of an artificial intelligence system, Advanced Process Expert (APE), developed by the Institute of High Performance Computing (IHPC). A prediction model to predict the melting points for the potential substrates was trained with the melting points of forty perovskite oxides obtained from literature. These forty training data were separated into two groups according to their melting points: group 1 if the melting point is larger than 1100°C, group 2 otherwise. With these, a good correlation between three basic elemental properties: atomic number, ionic radius and electro-negativity, was established. The developed correlation was employed to predict the melting points for the potential substrates.

The predicted melting points are all above 1100°C, indicating that the potential substrates, $SeCoO_3$, $SeNiO_3$, $SeMnO_3$, $TeCoO_3$, $TeNiO_3$, $TeMnO_3$, $SeZnO_3$, $SeCuO_3$ and $SeMgO_3$, satisfy the third criterion for the selection of a substrate.

Figure 2 illustrates a method 10 for selecting a substrate to grow a III-V nitride epilayer in accordance with another embodiment of the present invention. A physical property, for example, crystal structure, lattice mismatch, coefficient of thermal expansion or melting point, is selected in a block 12. Also selected, in a block 14, is a set of existing substrates for analysis. Thereafter, the physical property of each of the set of existing substrates is determined in a block 16 and analysed in a block 18 to establish a criterion for selecting the substrate. The physical property of a potential substrate is then determined in a decision block 20 to ascertain whether the potential substrate satisfies the criterion for selecting the substrate.

The potential substrate is rejected if the criterion is not satisfied. Otherwise, a decision is made in a decision block 22 on whether to accept the potential substrate as the substrate or to select in block 12 a further physical property to establish a further criterion for selecting the substrate.

The physical property selected in block 12 is preferably a lattice mismatch. The lattice mismatch of each of the set of existing substrates and the potential substrate may be obtained from literature.

Alternatively, the lattice mismatch may be determined by measuring a first atomic distance and a second atomic distance at a substrate-III-V nitride epilayer interface. The first atomic distance is between a pair of atoms on a cleavage plane, whereas the second atomic distance is between a pair of atoms on the III-V nitride epilayer. The lattice mismatch is then calculated from the first atomic distance and a second atomic distance, which are preferably the smallest first atomic distance and the smallest second atomic distance measured.

The further physical property may be a coefficient of thermal expansion or a melting point.

Figure 3 illustrates a schematic cross section of a semiconductor device 30 in accordance with yet another embodiment of the present invention. Semiconductor device 30 comprises a substrate 32 on which a III-V nitride epilayer 34 is provided. Successively provided on III-V nitride epilayer 34, which serves as an n-type contact layer, are an n-type barrier layer 36, an i-type active layer 38, a p-type barrier layer 40 and a p-type contact layer 42. III-V nitride epilayer 34 is further provided with an n-type electrode 44. Correspondingly, p-type contact layer 42 is provided with a p-type electrode 46.

Substrate 32 may have a perovskite structure. Examples of substrate 32 include $SeCoO_3$, $SeNiO_3$, $SeMnO_3$, $TeCoO_3$, $TeNiO_3$, $TeMnO_3$, $SeZnO_3$, $SeCuO_3$ and $SeMgO_3$.

Additionally, substrate 32 has preferably less than 13.8% lattice mismatch with III-V nitride epilayer 34, more preferably less than 6.96% lattice mismatch, and most preferably less than 0.06% lattice mismatch. Other preferred physical properties of

substrate 32 include a melting point greater than a processing temperature of the semiconductor device, and a coefficient of thermal expansion that differs from that of III-V nitride epilayer 34 by between about $\pm 1.9\times10^{-6}$ K^{-1}.

III-V nitride epilayer 34 may consist of a GaN semiconductor epitaxially grown on substrate 32. Further, III-V nitride epilayer 34 may be provided on a (010) cleavage plane of substrate 32 with only a single type of atoms.

Other embodiments of the invention will be apparent to those skilled in the art from consideration of the specification and practice of the invention. Furthermore, certain terminology has been used for the purposes of descriptive clarity, and not to limit the present invention. The embodiments and preferred features described above should be considered exemplary, with the invention being defined by the appended claims.

CLAIMS

1. A semiconductor device comprising:

a substrate having a perovskite structure; and

a III-V nitride epilayer provided on the substrate.

2. The semiconductor device as recited in claim 1, wherein the III-V nitride epilayer is provided on a cleavage plane of the substrate with only a single type of atoms.

3. The semiconductor device as recited in claim 1, wherein the substrate has a lattice mismatch of less than 13.8% with the III-V nitride epilayer.

4. The semiconductor device as recited in claim 1, wherein the substrate has a lattice mismatch of less than 6.96% with the III-V nitride epilayer.

5. The semiconductor device as recited in claim 1, wherein the substrate has a lattice mismatch of less than 0.06% with the III-V nitride epilayer.

6. The semiconductor device as recited in claim 3, wherein a coefficient of thermal expansion of the substrate differs from a coefficient of thermal expansion of the III-V nitride epilayer by between about $\pm 1.9 \times 10^{-6}$ K^{-1}.

7. The semiconductor device as recited in claim 6, wherein the substrate has a melting point greater than a processing temperature of the semiconductor device.

8. The semiconductor device as recited in claim 1, wherein the substrate is one of a group consisting of $SeCoO_3$, $SeNiO_3$, $SeMnO_3$, $TeCoO_3$, $TeNiO_3$, $TeMnO_3$, $SeZnO_3$, $SeCuO_3$ and $SeMgO_3$.

9. The semiconductor device as recited in claim 8, wherein the III-V nitride epilayer is provided on a (010) cleavage plane of the substrate.

10. The semiconductor device as recited in claim 9, wherein the III-V nitride epilayer is a GaN epilayer.

11. A semiconductor device comprising:

a substrate selected from a group consisting of $SeCoO_3$, $SeNiO_3$, $SeMnO_3$, $TeCoO_3$, $TeNiO_3$, $TeMnO_3$, $SeZnO_3$, $SeCuO_3$ and $SeMgO_3$; and

a III-V nitride epilayer provided on the substrate.

12. The semiconductor device as recited in claim 11, wherein the III-V nitride epilayer is provided on a cleavage plane of the substrate with only a single type of atoms.

13. The semiconductor device as recited in claim 11, wherein the substrate has a lattice mismatch of less than 13.8% with the III-V nitride epilayer.

14. The semiconductor device as recited in claim 11, wherein the substrate has a lattice mismatch of less than 6.96% with the III-V nitride epilayer.

15. The semiconductor device as recited in claim 11, wherein the substrate has a lattice mismatch of less than 0.06% with the III-V nitride epilayer.

16. The semiconductor device as recited in claim 13, wherein a coefficient of thermal expansion of the substrate differs from a coefficient of thermal expansion of the III-V nitride epilayer by between about $\pm 1.9\times10^{-6}\ K^{-1}$.

17. The semiconductor device as recited in claim 16, wherein the substrate has a melting point greater than a processing temperature of the semiconductor device.

18. The semiconductor device as recited in claim 11, wherein the III-V nitride epilayer is provided on a (010) cleavage plane of the substrate.

19. The semiconductor device as recited in claim 18, wherein the III-V nitride epilayer is a GaN epilayer.