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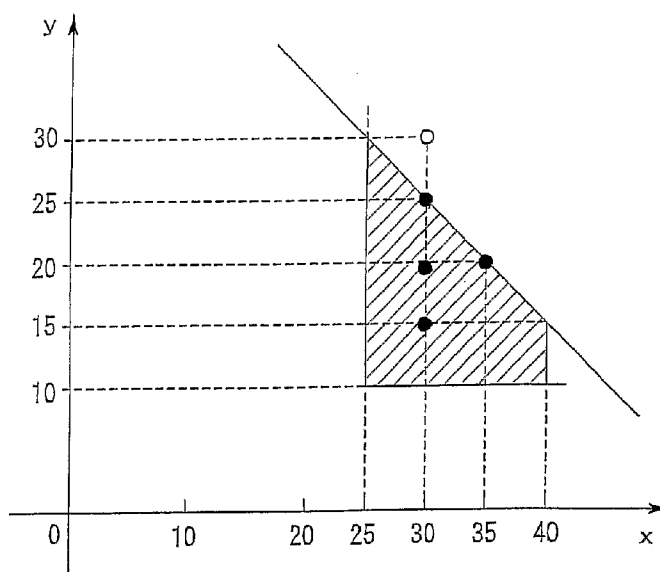
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(54) Title: SEMICONDUCTOR DEVICE



(57) Abstract: A semiconductor device having an AlGaN-GaN heterojunction structure including an AlGaN layer and a GaN layer which device exhibits no changes over time in sheet resistance. As shown in FIG. 1, in a semiconductor device having an Al-GaN-GaN heterojunction structure including an AlGaN layer 1 and a GaN layer 2, when the Al molar fraction of AlGaN (x%) and the thickness of the AlGaN layer (y nm) satisfy the relations: $x + y < 55$, $25 \leq x \leq 40$, and $y \geq 10$, y is smaller than the critical thickness, whereby no cracks are generated in the AlGaN layer. Therefore, the invention provides a semiconductor device exhibiting virtually no changes over time in sheet resistance despite high Al molar fraction.

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Description

Semiconductor Device

Technical Field

[0001]

The present invention relates to a group III nitride semiconductor device exhibiting little change over time in sheet resistance.

Background Art

[0002]

In recent years, group III nitride semiconductor materials have been remarkably developed through extensive studies thereon for application to LEDs and LDs. Recently, the semiconductor materials have been further studied for application to semiconductor devices other than LEDs and LDs, and application of the materials is now promising. By virtue of particular properties of a nitrogen atom, group III nitride semiconductors exhibit intense piezoelectric effect and spontaneous polarization. Therefore, in an AlGa_N-Ga_N heterojunction structure, the heterojunction interface can be imparted with a large 2-dimensional electron gas density without performing modulation doping; i.e., in a non-doped state. Thus, group III nitride semiconductors are promising materials for producing HEMT devices.

[0003]

One conceivable approach to enhance the 2-dimensional

electron gas density is to increase the Al molar fraction of AlGa_N, to thereby enhance piezoelectric effect. However, when this approach is employed to increase the 2-dimensional electron gas density, in some cases, an increase over time in sheet resistance of the AlGa_N layer is observed. Thus, electronic devices produced through such a technique fail to have reliability.

[0004]

The aforementioned changes over time in sheet resistance are conceivably caused by micro-cracks in AlGa_N growing as time passes. In other words, it is considered that as cracks propagate over time and reach the vicinity of the heterojunction interface, the surface area of AlGa_N increases on account of the increase of glide planes of the cracks. This promotes depletion of a surface energy level in the AlGa_N layer, whereby the density of the carriers is reduced, to thereby elevate sheet resistance. In addition, interception of current paths by cracking is conceived to be another reason for the increase in sheet resistance.

[0005]

A possible main reason for generation of cracks is that difference in lattice constants between AlGa_N and Ga_N provides strain and the strain increases as the thickness of the AlGa_N layer increases. When the thickness exceeds a certain value (referred to as a "critical thickness"), the thus-provided intolerable strain generates cracks in the layer.

[0006]

Therefore, one conceivable approach to prevent crack generation is to regulate the AlGa_N thickness to be equal to or less than the critical thickness.

Non-patent Document 1 discloses a theoretical formula for calculating the critical thickness. According to the formula, when the Poisson's ratios and lattice constants of AlGa_N and Ga_N are given, the critical thickness can be calculated. Notably, the Poisson's ratio and the lattice constants of AlGa_N vary in accordance with the Al molar fraction. Therefore, in the AlGa_N-Ga_N heterojunction structure, the critical thickness of the AlGa_N layer depends on the Al molar fraction of AlGa_N.

[0007]

Regarding the thickness of an AlGa_N layer, Patent Document 1 discloses a thickness of 25 nm when the Al molar fraction is 30%, and Patent Document 2 discloses a thickness of 25 nm when the Al molar fraction is 20%. However, both documents fail to teach the reason why the thickness is employed, and never describe changes over time in sheet resistance.

[0008]

Other approaches to prevent generation of cracks are also disclosed. Patent Document 3 discloses an approach through doping with magnesium, and Patent Document 4 discloses an approach through forming an AlN layer between an AlGa_N layer and a Ga_N layer.

Patent Document 1: Japanese Patent Application Laid-Open
(*kokai*) No. 2001-284576

Patent Document 2: Japanese Patent Application Laid-Open
(*kokai*) 2004-200248

Patent Document 3: Japanese Patent No. 3441329

Patent Document 4: Japanese Patent Application Laid-Open
(*kokai*) No. 2004-119783

Non-Patent Document 1: J. W. Matthews and A. E. Blakeslee, J.
Cryst. Growth, 27, 118 (1974)

Non-Patent Document 2: Polian, A., M. Grimsditch, I. Grzegory,
J. Appl. Phys. 79(6) (1996), 3343-3344

Non-Patent Document 3: Thokala, R, Chaudhuri J., Thin Solid
Films 266, 2 (1995), 189-191

Disclosure of the Invention

Problems to be Solved by the Invention

[0009]

However, attempts to calculate the critical thickness using the theoretical formula disclosed in Non-Patent Document 1 unexpectedly encounter difficulty. This is due to inconsistency among relevant academic societies in reporting values of material constants (e.g., Poisson's ratio and lattice constants) of AlGa_N and GaN crystals. These material constants vary depending on the crystal growth method, the epitaxial structure, or other factors. Therefore, the thus-calculated critical thickness values vary depending on the selected material constants, and the theoretical values do not correctly reflect actual critical thickness values.

[0010]

In a specific case, a lattice constant and Poisson's ratio of AlGa_N having an Al molar fraction of 30% are calculated through interpolation with the Vergard's law from, for example, a lattice constant of Ga_N of 5.185 and a Poisson's ratio of Ga_N of 0.352 (disclosed in Non-Patent Document 2) and a lattice constant of Al_N of 4.982 and a Poisson's ratio of Al_N of 0.287 (disclosed in Non-Patent Document 3). Through calculation on the basis of the theoretical formula disclosed in Non-Patent Document 1 from the thus-obtained lattice constant and Poisson's ratio, a critical thickness of the AlGa_N layer of 37 nm is obtained. Separately, changes over time in sheet resistance of an actual AlGa_N layer having an Al molar fraction of 30% and a thickness of 30 nm were observed. As shown in the graph given in FIG. 6, even though the AlGa_N layer has a thickness of 30 nm, which is smaller than the aforementioned critical thickness, sheet resistance was found to drastically increase after elapse of time of about 100 hours. This indicates that the thus-calculated theoretical value of critical thickness is considerably deviated from an actual value of critical thickness. Notably, in the graph given in FIG. 6, the lateral axis is represented by a logarithmic scale.

[0011]

Through repeated experiments, the present invention has been conceived on the basis of the existence of a specific relationship between the Al molar fraction of AlGa_N and the

critical thickness of an AlGa_N layer. Thus, an object of the invention is to realize a semiconductor device which has an AlGa_N-Ga_N heterojunction structure and which exhibits small changes over time in sheet resistance, through regulating the thickness of the AlGa_N layer to be equal to or less than the critical thickness.

Another object of the invention is to realize a semiconductor device which has an AlGa_N-Ga_N heterojunction structure and which exhibits small changes over time in sheet resistance, through employment of a novel structure.

Means for Solving the Problems

[0012]

In a first aspect of the present invention, there is provided a semiconductor device having an AlGa_N-Ga_N heterojunction structure including an AlGa_N layer and a Ga_N layer, characterized in that the AlGa_N layer has an Al molar fraction (x%) and a thickness (y nm), wherein x and y satisfy the following relations: $x + y < 55$, $25 \leq x \leq 40$, and $y \geq 10$.

[0013]

The value of y calculated from the equation: $y = 55 - x$ corresponds to the critical thickness of an AlGa_N layer having an Al molar fraction of x%. The critical thickness has been first obtained through repeated experiments. When the Al molar fraction and the thickness fall within the ranges of the first aspect of the invention, the AlGa_N layer has a thickness smaller than the critical thickness. The condition $y \geq 10$ is employed, since if the thickness is less

than 10 nm, uniform film is difficult to form, and pits, which increase resistance, may be generated. The AlGa_N layer and the Ga_N layer may be doped with an impurity element such as Mg. The parameter "x" preferably falls within the range: $25 \leq x \leq 40$, most preferably $30 \leq x \leq 35$. The condition $x \geq 40$ is not preferred, since the critical thickness is excessively small in the range, and a uniform AlGa_N layer is difficult to form.

[0014]

In a second aspect of the present invention, there is provided a semiconductor device having an AlGa_N-Ga_N heterojunction structure including an AlGa_N layer and a Ga_N layer, characterized in that the device has an intrinsic Ga_N layer (hereinafter referred to as i-Ga_N layer) on a surface of the AlGa_N layer opposite the surface of the AlGa_N layer to which the Ga_N layer has been joined, that the AlGa_N layer has an Al molar fraction of 30% to 40% and a thickness of 30 nm to 45 nm, and that the i-Ga_N layer has a thickness of 5 nm to 100 nm.

[0015]

The second aspect of the invention is preferred for increasing the thickness of the AlGa_N layer while the Al molar fraction is maintained at a high level. Specifically, the thickness can be increased to 30 nm or more at an Al molar fraction of $\geq 30\%$, whereby the thickness of the AlGa_N layer can exceed the critical thickness. In a third aspect of the present invention, the i-Ga_N layer preferably has a

thickness of 20 nm or less. A thickness of 100 nm or more of the i-GaN layer is not preferred, since strain in AlGaN is excessively relaxed, and an Ohmic electrode is difficult to form on the i-GaN layer. Thus, the i-GaN layer preferably has a thickness of 5 nm or more. When the thickness is less than 5 nm, effect of relaxing the strain fails to be attained. The Al molar fraction is preferably 40% or less, and the AlGaN layer preferably has a thickness of 40 nm or less. In a fourth aspect of the invention, the AlGaN layer is joined to the i-GaN layer. Needless to say, the two layers are not necessarily joined to each other. For example, a metallic film may intervene between the AlGaN layer and the i-GaN layer. In the second to fourth aspects of the invention, similar to the first aspect, the AlGaN layer and the GaN layer may be doped.

[0016]

In a fifth aspect of the invention, there is provided an HEMT employing a device of the first aspect. In a sixth aspect, there is provided an HEMT employing a device of any of the second to fourth aspects.

Effects of the Invention

[0017]

According to the semiconductor device of the first aspect of the invention, the AlGaN layer has a thickness smaller than the critical thickness determined through experiments. Therefore, generation of cracks and changes over time in sheet resistance are prevented.

[0018]

The semiconductor device of the second aspect of the invention is provided with an i-GaN layer (intrinsic GaN layer). Thus, even though the AlGaN layer has a thickness greater than the critical thickness, strain in the AlGaN layer can be compensated, to thereby prevent generation of cracks. Similar to the first aspect of the invention, the semiconductor device exhibits small changes over time in sheet resistance.

[0019]

An HEMT device produced from the semiconductor device according to the present invention has a high Al molar fraction. Therefore, high 2-dimensional electron gas density at an heterojunction interface can be attained, whereby a useful HEMT device which does not exhibit deterioration in performance over time can be produced.

Best Modes for Carrying Out the Invention

[0020]

With reference to the drawings, the present invention will next be described in detail by way of examples, which should not be construed as limiting the invention thereto.

Example 1

[0021]

In Example 1, a semiconductor device as shown in FIG. 1 having a heterojunction structure formed from an AlGaN layer 1 and a GaN layer 2 was produced. Similar semiconductor devices having different Al molar fractions and thicknesses

of the AlGa_N layer 1 were also produced, and changes over time in sheet resistance were observed for the produced devices.

[0022]

In Example 1, each semiconductor device was produced by forming, through MOCVD, an AlN buffer layer 3 on an SiC substrate 4, a Ga_N layer 2 on the buffer layer, and an AlGa_N layer 1 on the Ga_N layer. The AlGa_N layer 1 and the Ga_N layer 2 were non-doped. The Ga_N layer 2 had a thickness of 2 μm .

[0023]

Specifically, four devices (Al molar fraction: 30%, thickness of AlGa_N layer 1: 15, 20, and 25 nm, and Al molar fraction: 35%, thickness of AlGa_N layer 1: 20 nm) were produced. Changes over time in sheet resistance were monitored for the four devices. The results are shown in the graph given in FIG. 2. In FIG. 2, sheet resistance values of the device (Al molar fraction: 30%, thickness: 15 nm) are represented by triangles; those of the device (Al molar fraction: 30%, thickness: 20 nm) are represented by squares; those of the device (Al molar fraction: 30%, thickness: 25 nm) are represented by circles; and those of the device (Al molar fraction: 35%, thickness: 20 nm) are represented by inverted triangles. As shown in the graph given in FIG. 2, tested devices (Al molar fraction: 30%, thickness: 15, 20, and 25 nm) exhibited substantially no changes in sheet resistance over about 10 days, and a tested device (Al molar

fraction: 35%, thickness: 20 nm) exhibited substantially no changes in sheet resistance over about 40 days. In each case, measured resistance values varied slightly. However, the tested devices did not exhibit significant increase in sheet resistance, which had been observed for conventional devices about 100 hours after the start of the test as shown in the graph given in FIG. 6. The slight variations in measured resistance values may be attributable to temperature variation by about 1°C to 2°C at the measurement and are not caused by generation of cracks.

[0024]

Data of the Al molar fraction (x%) of the AlGa_N layer 1 and the thickness (y nm) of the AlGa_N layer 1 given in FIGs. 2 and 6 were plotted in a graph with a lateral axis (x) and a vertical axis (y) shown in FIG. 3. In FIG. 3, data sets (x, y) in which no changes over time in sheet resistance were observed are represented by black circles, whereas a data set (x, y) in which changes over time in sheet resistance were observed is represented by a white circle. Thus, semiconductor devices exhibiting a data set falling within a slant-lined area shown in FIG. 3 are conceived to exhibit no changes over time in sheet resistance.

Example 2

[0025]

In Example 2, a semiconductor device as shown in FIG. 4 having a structure having an AlGa_N layer 1 joined to the upper surface of a Ga_N layer 2, and an i-Ga_N layer 5, i.e., an

intrinsic or un-doped GaN layer, joined to the upper surface of the AlGaIn layer 1 was produced. The AlGaIn layer 1, GaN layer 2, and GaN layer 5 are un-doped, i.e., intrinsic. The GaN layer 2 has a thickness of 2 μm , the AlGaIn layer 1 has an Al molar fraction of 30% and a thickness of 30 nm, and the i-GaN layer 5 has a thickness of 75 nm.

[0026]

Changes over time in sheet resistance were monitored in a manner similar to that of Example 1, and the results are shown in FIG. 5. Similar to Example 1, although the measured sheet resistance values have slight variations conceivably due to temperature variation, no significant changes in sheet resistance were observed from hour 300 to hour 500, after production of the test device.

Industrial Applicability

[0027]

The semiconductor device of the present invention can be employed for producing semiconductor devices such as HEMT devices, and can prolong the service life of the semiconductor devices produced therefrom.

Brief Description of the Drawings

[0028]

[FIG. 1] A semiconductor device of Example 1.

[FIG. 2] A graph showing changes over time in sheet resistance of the semiconductor devices produced in Example 1.

[FIG. 3] A graph showing the relation between the Al molar fraction of the AlGaIn layer and the thickness of the AlGaIn

layer, specifying the area where the semiconductor devices exhibits no changes over time in sheet resistance.

[FIG. 4] A semiconductor device of Example 2.

[FIG. 5] A graph showing changes over time in sheet resistance of the semiconductor device produced in Example 2.

[FIG. 6] A graph showing changes over time in sheet resistance of a semiconductor device.

Description of Reference Numerals

[0029]

1: AlGaN layer

2: GaN layer

3: Buffer layer

4: SiC substrate

5: GaN layer

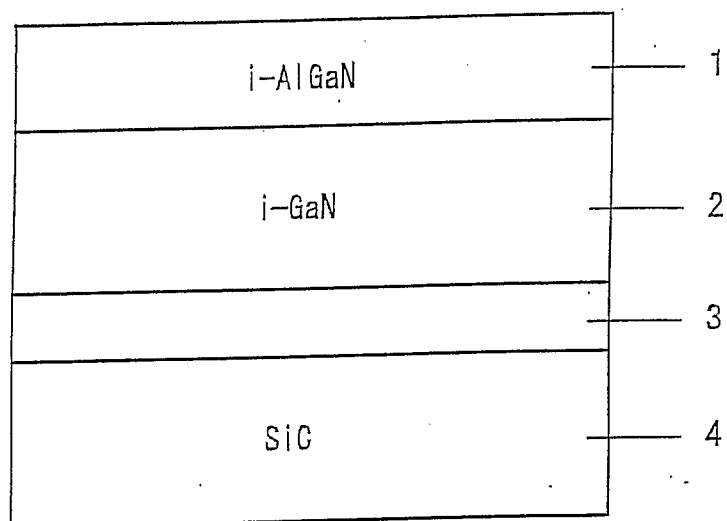
Claims

- [1] A semiconductor device having an AlGa_N-Ga_N heterojunction structure including an AlGa_N layer and a Ga_N layer, characterized in that the AlGa_N layer has an Al molar fraction (x%) and a thickness (y nm), wherein x and y satisfy the following relations: $x + y < 55$, $25 \leq x \leq 40$, and $y \geq 10$.
- [2] A semiconductor device having an AlGa_N-Ga_N heterojunction structure including an AlGa_N layer and a Ga_N layer, characterized in that the device has an intrinsic i-Ga_N layer on a surface of the AlGa_N layer opposite the surface of the AlGa_N layer to which the Ga_N layer has been joined, that the AlGa_N layer has an Al molar fraction of 30% to 40% and a thickness of 30 nm to 45 nm, and that the intrinsic i-Ga_N layer has a thickness of 5 nm to 100 nm.
- [3] A semiconductor device as described in claim 2, wherein the an intrinsic i-Ga_N layer has a thickness of 5 nm to 20 nm.
- [4] A semiconductor device as described in claim 2 or 3, wherein the AlGa_N layer and the intrinsic i-Ga_N layer are joined to each other.
- [5] A semiconductor device as described in claim 1, which is an HEMT, wherein
- the AlGa_N layer serves as a barrier layer,
 - the Ga_N layer serves as a channel layer, and
 - 2-dimensional electron gas is formed at the junction interface between the AlGa_N layer and the Ga_N layer.
- [6] A semiconductor device as described in any one of claims 2 to 4, which is an HEMT, wherein

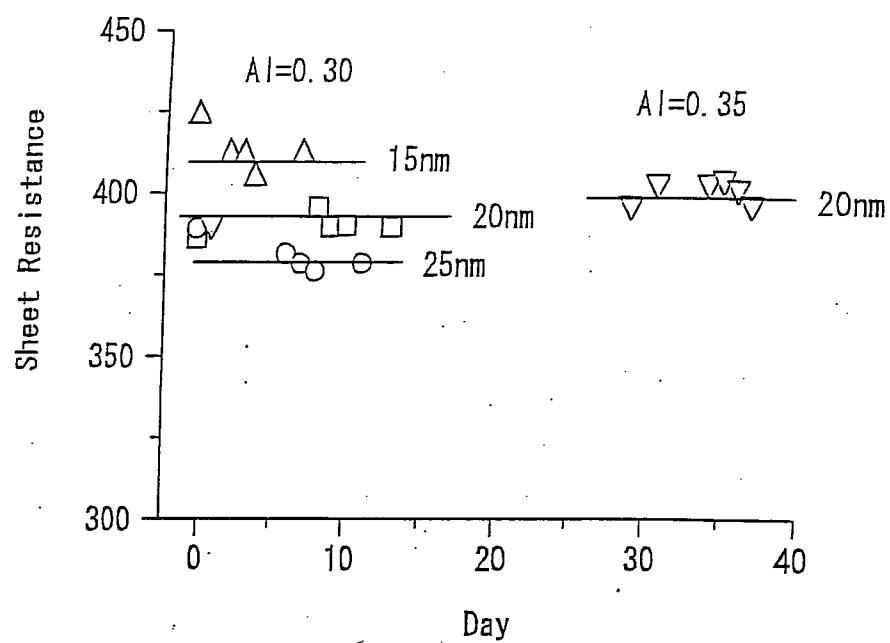
the AlGa_N layer serves as a barrier layer,
the Ga_N layer serves as a channel layer,
the intrinsic i-Ga_N layer serves as a capping layer,
and

2-dimensional electron gas is formed at the junction
interface between the AlGa_N layer and the Ga_N layer.

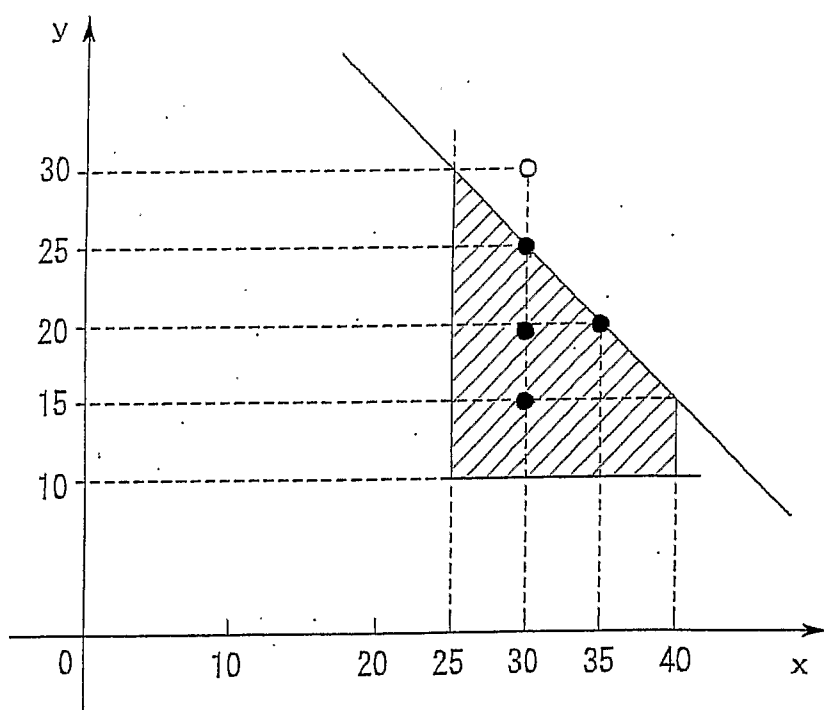
【Fig. 1】



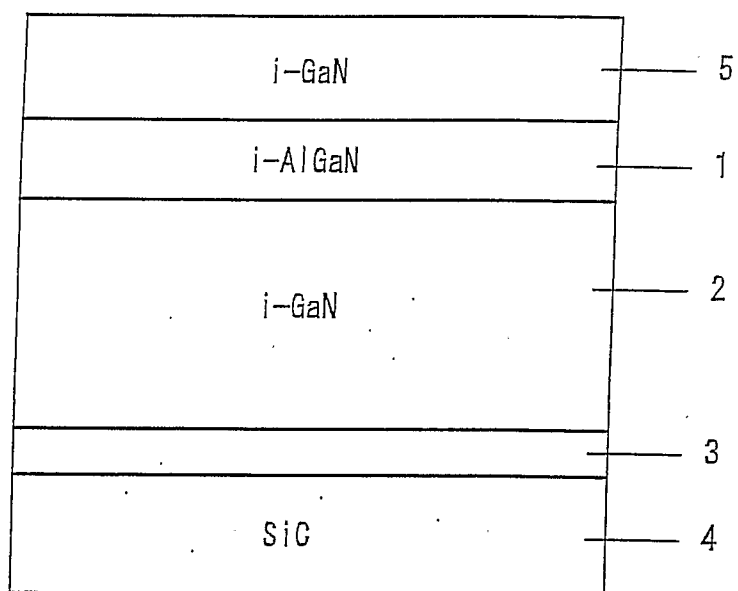
[Fig. 2]



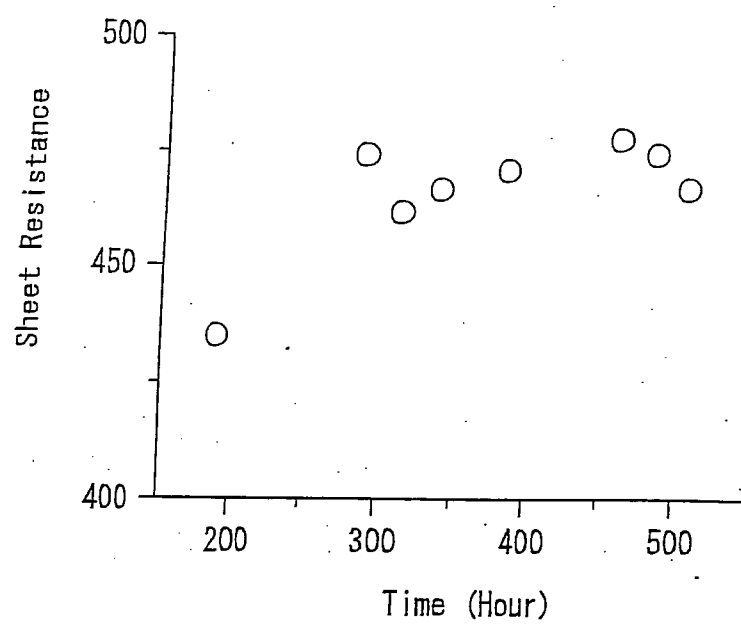
【Fig. 3】



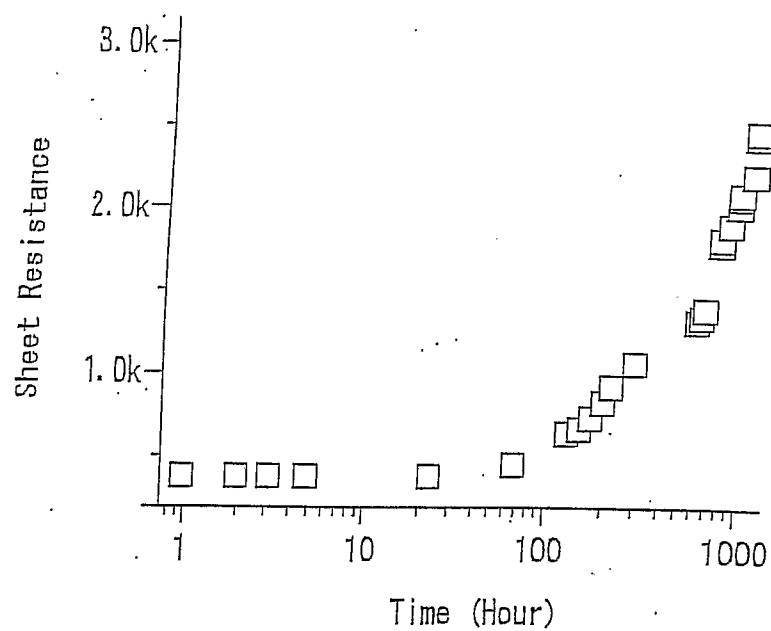
【Fig. 4】



【Fig. 5】



[Fig. 6]



INTERNATIONALSEARCHREPORT

International application No.

PCT/JP2007/061412

A. CLASSIFICATION OF SUBJECT MATTER

Int.Cl. H01L21/338 (2006.01) i, H01L21/205 (2006.01) i, H01L29/201 (2006.01) i,
H01L29/778 (2006.01) i, H01L29/812 (2006.01) i

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Int.Cl. H01L21/338, H01L21/205, H01L29/201, H01L29/778, H01L29/812

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

Published examined utility model applications of Japan 1922-1996
Published unexamined utility model applications of Japan 1971-2007
Registered utility model specifications of Japan 1996-2007
Published registered utility model applications of Japan 1994-2007

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 2006-059956 A (MATSUSHITA ELECTRIC INDUSTRIAL CO., LTD.) 2006.03.02, Paragraph 【0014】, Fig 1 (Family: none)	1, 5
X	US 2005/0189651 A1 (MATSUSHITA ELECTRIC INDUSTRIAL CO., LTD.) 2005.09.01, Paragraph [0036]-[0037], Fig 1 & JP 2004-111910 A	1, 5
Y	US 2004/0232440 A1 (SANKEN ELECTRIC CO., LTD.) 2004.11.25, Fig 5 & JP 2004-349387 A	2, 3, 4, 6
Y	JP 2002-359256 A (Fujitsu CO., LTD.) 2002.12.13, Fig 5 (Family: none)	2, 3, 4, 6

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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Date of the actual completion of the international search

06.08.2007

Date of mailing of the international search report

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INTERNATIONALSEARCHREPORT

International application No.

PCT/JP2007/061412

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP 2004-335960 A (KRI CO., LTD.) 2004.11.25, Fig 1 (Family: none)	2, 3, 4, 6