(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
1 July 2010 (01.07.2010)

PCT

(10) International Publication Number
WO 2010/075124 A1

(51) International Patent Classification:
H01L 21/335 (2006.01) *H01L 29/778* (2006.01)
H01L 29/267 (2006.01) *H01L 29/16* (2006.01)

(21) International Application Number:
PCT/US2009/068178

(22) International Filing Date:
16 December 2009 (16.12.2009)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
12/341,191 22 December 2008 (22.12.2008) US

(71) Applicant *(for all designated States except US)*: **RAYTHEON COMPANY** [US/US]; 870 Winter Street, Waltham, MA 02451-1449 (US).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **KORENSTEIN, Ralph** [US/US]; 375 Singletary Lane, Framingham, MA 01702 (US). **BERNSTEIN, Steven, D.** [US/US]; 42 Dustin Street, Brighton, MA 02135 (US). **PEREIRA, Stephen, J.** [US/US]; 11 Ballou Road, Hopedale, MA 01747-1833 (US).

(74) Agents: **MOOSEY, Anthony, T.** et al.; Daly, Crowley, Mofford & Durkee, LLP, Suite 301A, 354A Turnpike St., Canton, MA 02021 (US).

[Continued on next page]

(54) Title: FABRICATING A GALLIUM NITRIDE LAYER WITH DIAMOND LAYERS

(57) Abstract: In one aspect, a method includes fabricating a gallium nitride (GaN) layer with a first diamond layer having a first thermal conductivity and a second diamond layer having a second thermal conductivity greater than the first thermal conductivity. The fabricating includes using a microwave plasma chemical vapor deposition (CVD) process to deposit the second diamond layer onto the first diamond layer.

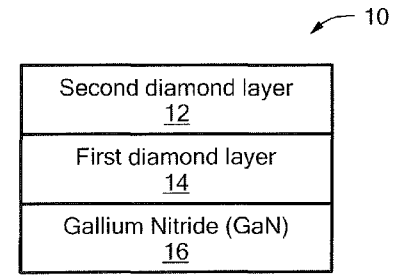


FIG. 1A

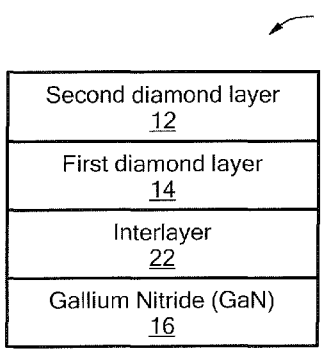


FIG. 1B

WO 2010/075124 A1

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

Published:

— *with international search report (Art. 21(3))*

FABRICATING A GALLIUM NITRIDE LAYER WITH DIAMOND LAYERS

BACKGROUND

Gallium Nitride (GaN) has electrical and physical properties that make it highly suitable for high frequency (HF) devices such as microwave devices. The HF devices produce a high amount of heat requiring a heat spreader to be attached to the HF devices to avoid device failure. One such heat spreader is diamond. A hot filament chemical vapor deposition (CVD) process has been used to form diamond that is used on GaN layers. Generally, these diamond layers are not deposited directly onto the GaN layers but onto some other material (e.g., silicon, silicon carbide, and so forth) that is eventually disposed with the GaN layer.

SUMMARY

In one aspect, a method includes fabricating a gallium nitride (GaN) layer with a first diamond layer having a first thermal conductivity and a second diamond layer having a second thermal conductivity greater than the first thermal conductivity. The fabricating includes using a microwave plasma chemical vapor deposition (CVD) process to deposit the second diamond layer onto the first diamond layer.

In another aspect, a method includes fabricating a gallium nitride (GaN) layer with a first diamond layer having a first thermal conductivity and a second diamond layer having a second thermal conductivity greater than the first thermal conductivity. The fabricating includes using a microwave plasma chemical vapor deposition (CVD) process to deposit the second diamond layer of between about 2 mils to about 4 mils on the first diamond layer of less than about 1 mil.

In a further aspect, a device includes a gallium nitride (GaN) layer, a first layer of diamond having a first thermal conductivity disposed on the GaN layer and a second layer of diamond having a second thermal conductivity twice the first thermal conductivity deposited on the first layer of diamond.

DESCRIPTION OF THE DRAWINGS

FIG. 1A is a diagram of an example of a Gallium Nitride (GaN) layer with a first diamond layer and a second diamond layer.

FIG. 1B is a diagram of another example of the GaN layer with the first diamond layer and the second diamond layer.

FIG. 2 is a flowchart of an example of a process to fabricate the GaN layer with the first diamond layer and the second diamond layer.

FIGS. 3A to 3D are diagrams corresponding to the process of FIG. 2.

FIG. 4 is a flowchart of another example of a process to fabricate a GaN layer with the first diamond layer and the second diamond layer.

FIGS. 5A to 5H are diagrams corresponding to the process of FIG. 4.

FIG. 6 is a flowchart of an example of a process for depositing diamond on another surface.

FIGS. 7A to 7F are diagrams corresponding to the process of FIG. 6.

FIG. 8 is a flowchart of another example of a process for depositing diamond on another surface.

FIGS. 9A to 9D are diagrams corresponding to the process of FIG. 6.

FIG. 10 is an example of a device with diamond layers.

FIG. 11 is another example of a device with diamond layers.

FIG. 12 is a graph depicting thermal performance with diamond coatings.

DETAILED DESCRIPTION

Hot filament chemical vapor deposition (CVD) processes have been used to form diamond layers of less than 1 mil that are used on gallium nitride (GaN) layers. To be effective as a heat spreader, diamond layers must be greater than 2 mils. Moreover, the hot filament CVD process by its very nature produces a blackish-color diamond which is contaminated with material used in the hot filament CVD process such as tungsten, for example. In general, these "dirty" diamond layers that are produced have a lower thermal conductivity than pure diamond. In general, the thermal conductivity of diamond layers using the hot filament CVD process is about 800 to 1000 Watts/meter – Kelvin (W/m-K).

A microwave plasma CVD process has been known to produce much thicker diamond layers on the order of 4 mils or greater at a much faster rate than the hot filament CVD process. Moreover the diamond layers are purer than the hot filament CVD process producing diamond layers having a thermal conductivity greater than 1500 W/m-K. In one example, the thermal conductivity of diamond produced using the microwave plasma CVD process is twice the thermal conductivity of diamond produced using the hot filament process. However, the CVD processes including the microwave plasma CVD process is relatively unknown with respect to direct deposition onto GaN. For example, the deposition of diamond using hot filament CVD is typically done onto some other material (e.g., silicon, silicon carbide, and so forth) that is eventually is disposed with the GaN layer. Since the deposition of diamond directly onto to GaN using the microwave plasma CVD process is

relatively unknown, the costs of developing and testing a reliable and successful processes to deposit diamond directly onto the GaN is extremely expensive. One way around the cost and expense of developing a process to deposit diamond directly onto GaN, is to deposit diamond using the microwave plasma CVD process onto an inferior diamond layer that was fabricated using the hot filament CVD, for example.

As used herein GaN layers may include pure GaN, doped GaN or GaN combined with other elements (e.g., AlGaN) or any combination thereof. Silicon substrates may include pure silicon, doped silicon, silicon dioxide, silicon carbide or any combination of silicon with other elements or any combination thereof.

Referring to FIGS. 1A and 1B, in one example, a structure 10 for use in forming a device (e.g., a high frequency device, a high electron mobility transistor (HEMT), a microwave device and so forth) includes a second diamond layer 12, a first diamond layer 14 adjacent to the second diamond layer and a GaN layer 16 adjacent to the first diamond layer. In this configuration, heat produced by GaN layer 16 pass through a heat spreader formed by the first and second diamond layers 12, 14. In another example, a structure 20 uses to form a device (e.g., a high frequency device, a HEMT transistor, a microwave device and so forth) is similar to the structure 10 but includes an interlayer 22 between the first diamond layer and the GaN layer 16. The interlayer 22 is needed because the fabrication of diamond directly onto GaN is not easy process much less predictable or consistent. The interlayer 22 may be simply an adhesive holding the first diamond layer 14 to the GaN 16 or a silicon-type structure onto which diamond may easily be disposed. Sometimes the interlayer 22 has a thermal conductivity less than that of the diamond

layers 12, 14 so that it holds heat more; or put another way, the heat transference from the GaN layer 16 is impeded by the interlayer 22. Thus, minimizing the interlayer 22 or not having the interlayer at all as in the structure 10 is preferred.

Referring to FIGS. 2 and 3A to 3D, one process to fabricate a GaN layer with a first diamond layer and a second diamond layer is a process 100. The hot filament CVD process is used to deposit a first diamond layer 14 (e.g., a layer of 5 to 20 microns thick) onto a silicon-on-insulator (SOI) substrate 122 (102) (FIG. 3A). The insulator (not shown) (e.g., silicon dioxide) is removed from the SOI substrate 122 leaving a silicon substrate 122', for example (104) (FIG. 3B). The microwave plasma CVD is used to deposit a second diamond layer 12 onto the first diamond layer 14 (108) (FIG. 3C). GaN is grown onto the remaining SOI substrate, the silicon substrate 122 (112) (FIG. 3D).

Referring to FIGS. 4 and 5A to 5H, another process to fabricate a GaN layer with a first diamond layer and a second diamond layer is a process 200. GaN 16 is grown on a first substrate 230 (202) (FIG. 5A). In one example, the first substrate may be silicon carbide, silicon or sapphire. A silicon layer 232 (e.g., silicon, silicon carbide and so forth) is disposed onto the GaN (204) (FIG. 5B). In one example, the silicon layer 232 is attached to the GaN 16 using an adhesive. In another example, the silicon layer 232 is grown onto the GaN 16. In other examples, other materials such as glass may be used instead of the silicon layer 232. The first substrate 230 is removed (208), for example, through etching leaving a GaN/silicon structure 250 (FIG. 5C). A hot filament CVD is used to deposit a first layer of diamond 14 onto a second substrate 234 (212) (FIG. 5D). For example, the second substrate 234 is a silicon substrate 500 microns thick. A microwave plasma CVD process is used to

deposit a second diamond layer 12 onto the first diamond layer 14 (218) (FIG. 5E). The second substrate 234 is removed (218), for example, through etching (FIG. 5F). The first and second diamond layers 12, 14 are attached to the GaN/silicon structure 250 (224) (FIG. 5G). For example, the first diamond layer 14 is attached to the GaN 16 using an adhesive. The silicon layer 232 is removed (228), for example, through etching (FIG. 5H).

Referring to FIG. 6 and 7A to 7F, a further process to fabricate a GaN layer with diamond layers is a process 300. Process 300 is similar to process 200 except a third diamond layer 316 is disposed on a first GaN surface 302 (e.g., a top surface) (FIG. 7F) opposite a second GaN surface 304 (e.g., a bottom surface) (FIG.7F) that has the first and second diamond layers 14, 12. For example, processing blocks 202, 204 and 208 are performed as in process 200. In particular, the GaN 16 is grown on the first substrate 230 (202) (FIG. 7A), the silicon layer 232 is disposed onto the GaN 16 (204) (FIG. 7B); and the first substrate 230 is removed (208), for example, through etching leaving the GaN/silicon structure 250 (FIG. 7C).

The silicon/GaN structure 250 is immersed in a solution and subjected to ultrasound (302). By treating the surface prior to deposition (e.g., a processing block 314), the diamond layer 316 has a better chance of forming on the GaN 16 during deposition. In one example, the solution is an isopropyl alcohol solution that includes diamond particles (e.g., nano-diamond particles (10^{-9} m)).

The third diamond layer 316 is disposed on the silicon/GaN structure 250 (314) (FIG. 7D). For example, the microwave plasma CVD process is used to deposit the third diamond layer 316 onto the GaN 250 at temperatures from about

600 °C to about 650 °C. The silicon layer 232 is removed (228), for example, through etching (FIG. 7E).

The first and second diamond layers 14, 12, formed using process blocks 212, 214 and 218, for example, are attached to the remaining GaN/diamond structure to form a diamond/GaN/diamond/diamond structure 360 (334) (FIG. 7F). For example, the first diamond layer 14 is attached to the GaN 16 using an adhesive. The first diamond layer 14 is attached to the second surface 304 opposite to the first surface 302 disposed with the third diamond layer 316. By having a diamond layer 316 disposed on opposite surfaces from the diamond layers 12, 14, heat is more effectively pulled away from devices formed from the diamond/GaN/diamond/diamond structure 360.

Referring to FIG. 8 and 9A to 9D, a still further process to fabricate a GaN layer with diamond layers is a process 370. A silicon carbide/GaN structure 380 (FIG. 9A) that includes a GaN layer 16 and a silicon carbide layer 382 disposed with the second surface of the GaN 16. The silicon carbide/GaN structure 380 is immersed in an isopropyl alcohol solution with nano-diamond particles (e.g., a solution used in processing block 312) and an ultrasound is performed (372). A third diamond layer 316 is disposed on the GaN 16 (374) (FIG. 9B). The silicon carbide layer 382 is removed, for example, through etching (376) (FIG. 9C). The first and second diamond layers 14, 12 are formed using processing blocks 212, 214, and 218, for example. The first and second diamond layers 14, 12 are attached to the GaN/diamond 350 to form the diamond/GaN/diamond/diamond structure 360 (334) (FIG. 9D).

Referring to FIG. 10, the diamond/GaN/diamond/diamond structure 360 may be used to fabricate devices such as a high frequency device, a high electron mobility transistor (HEMT), a microwave device and so forth. For example, the diamond layer 316 may be integrated directly into the devices and used not only to remove heat but function as a dielectric, for example, used in capacitance. For example, the dielectric constant of diamond is about 5.7 which is close to the dielectric constant of about 7 for silicon nitride films commonly used in GaN devices; however, diamond films have a greater thermal conductivity than the silicon nitride films. In some examples, portions of the diamond layer 316 are removed (e.g., using oxygen plasma) and the surface 302 of the GaN 16 becomes exposed.

In one example, a device 400 (e.g., a HEMT device) includes a source 404, a drain 406 and a gate 408 (e.g., a T-Gate) that are deposited in a metallization step onto to the surface 302 of the GaN layer 16. The gate 408 is formed in the diamond layer 316 after removal of portions of the diamond layer thereby exposing the GaN. In this example, the removal of portions of the diamond layer 316 splits the diamond layer into two diamond layers 316a, 316b each having a width W. In this configuration, the diamond layers 316a, 316b may function as a dielectric layer and a heat spreader by removing the heat away from the gate 408. In some examples, the widths of the diamond layers 316a, 316b may not be equal. In one example, portions of the gate 408 are adjacent to and in contact with the diamond layers 316a, 316b and other portions of the gate 408 form gaps 410a, 410b (e.g., air gaps) between the gate and the diamond layers 316a, 316b. In one example, gate 408, the gaps 410a, 410b, the diamond layer 316a, 316b form capacitance structures. One of

ordinary skill in the art would be aware of several methods to form these gaps 410a, 410b. For example, prior to metallization to form the gate 408, a material (e.g., photoresist) may be on the surface of the diamond layer 316. After the gate 408 is formed, the material is removed forming the gaps 410a, 410b. In other examples, the device 400 does not include gaps 410a, 410b so that the gate 408 is directly on the surface of the diamond layers 316a, 316b. In still further examples, other materials may fill gaps 410a, 410b that may or may not contribute to capacitance.

Referring to FIGS. 11 and 12, a device 400' is similar to the device 400 with the GaN layer 16 including an AlGaN layer 412 and a pure GaN layer 416. Other GaN-type materials may be added to the GaN layer 416 than the AlGaN 412. The GaN layer 416 may also be replaced with doped GaN or other GaN-type materials. The third diamond layers 316a, 316b are used to significantly reduce temperatures at the gate 408 by spreading the heat away from the gate. A graph 500 depicts the effects of heat as a function of the width, W, of the diamond layer 316a or 316b using the device 400'. A distance, D, between the gate 408 and the source 404 is 1.875 microns and a distance, G, between the diamond layers 316a, 316b is .25 microns. A curve 502 represents a .05 micron layer of diamond and a curve 504 represents a .25 micron layer of diamond. The .25 micron diamond coating allows a 20% increase in output power and reduces thermal resistance by 15% (>25°C at 5 W/mm) than not having a diamond layers 316a, 316b. The .05 micron diamond coating reduces thermal resistance by 10% (>25°C at 5 W/mm) than not having a diamond layers 316a, 316b.

The processes described herein are not limited to the specific embodiments described herein. For example, the processes are not limited to the specific

processing order of the process steps in FIGS. 2, 4, 6 and 8. Rather, any of the processing steps of FIGS. 2, 4, 6 and 8 may be re-ordered, combined or removed, performed in parallel or in serial, as necessary, to achieve the results set forth above.

While the invention is shown and described in conjunction with a particular embodiment having an illustrative product having certain components in a given order, it is understood that other embodiments well within the scope of the invention are contemplated having more and fewer components, having different types of components, and being coupled in various arrangements. Such embodiments will be readily apparent to one of ordinary skill in the art. Other embodiments not specifically described herein are also within the scope of the following claims.

What is claimed is:

1. A method, comprising:

fabricating a gallium nitride (GaN) layer with a first diamond layer having a first thermal conductivity and a second diamond layer having a second thermal conductivity greater than the first thermal conductivity, the fabricating comprising:

using a microwave plasma chemical vapor deposition (CVD) process to deposit the second diamond layer onto the first diamond layer.

2. The method of claim 1 wherein using a microwave plasma chemical vapor deposition (CVD) process to deposit the second diamond layer on the first diamond layer comprises using a microwave plasma chemical vapor deposition (CVD) process to deposit the second diamond layer is about 2 mils.

3. The method of claim 2 wherein using a microwave plasma chemical vapor deposition (CVD) process to deposit the second diamond layer on the first diamond layer comprises using a microwave plasma chemical vapor deposition (CVD) process to deposit the second diamond layer is about 2 mils on the first diamond layer less than about 1mil.

4. The method of claim 1 wherein using a microwave plasma chemical vapor deposition (CVD) process to deposit the second diamond layer on the first diamond layer comprises using a microwave plasma chemical vapor deposition (CVD) process to deposit the second diamond layer is about 4 mils.

5. The method of claim 1 wherein fabricating a gallium nitride (GaN) layer with a first diamond layer having a first thermal conductivity and a second diamond layer having a second thermal conductivity greater than the first thermal conductivity comprises fabricating a gallium nitride (GaN) layer with a first diamond layer having a first thermal conductivity and a second diamond layer having a second thermal conductivity twice the first thermal conductivity.

6. The method of claim 1 wherein the fabricating further comprises using a hot filament CVD process to form the first diamond layer.

7. The method of claim 1 wherein the fabricating further comprises growing the GaN layer on a first substrate.

8. The method of claim 7 wherein growing the GaN layer on a first substrate comprises growing the GaN layer on one of silicon carbide, silicon or sapphire.

9. The method of claim 7 wherein the fabricating further comprises:

disposing a layer of material onto the GaN layer; and

removing the first substrate.

10. The method of claim 9 wherein disposing a layer of material onto the GaN layer comprises disposing one of a silicon layer or a glass layer.

11. The method of claim 9 wherein the fabricating further comprises:

depositing the first diamond layer on a second substrate; and

removing the second substrate.

12. The method of claim 11 wherein depositing the first diamond layer on a second substrate comprises depositing the first diamond layer on a silicon substrate

13. The method of claim 11 wherein the fabricating further comprises:

attaching the first and second diamond layers to the GaN layer; and

removing the layer of material.

14. The method of claim 1 wherein the fabricating further comprises:

depositing the first diamond layer on to a silicon-on-insulator (SOI) substrate;

removing an oxide from the SOI substrate; and

growing the GaN layer on remaining SOI substrate.

15. The method of claim 1 wherein fabricating a gallium nitride (GaN) layer with a first diamond layer comprises disposing the first diamond layer on a first surface of the GaN, and

further comprising disposing a third diamond layer on a second surface of the GaN layer opposite the first surface of the GaN layer.

16. The method of claim 1 wherein fabricating a gallium nitride (GaN) layer with a first diamond layer having a first thermal conductivity and a second diamond

layer having a second thermal conductivity greater than the first thermal conductivity comprises fabricating a GaN layer comprising at least one of undoped GaN, doped GaN or GaN combined with another element.

17. The method of claim 1, further comprising fabricating at least one of a high frequency device, a high electron mobility transistor (HEMT) or a microwave device from the gallium nitride (GaN) layer with the first diamond and the second diamond layer.

18. A method, comprising:

fabricating a gallium nitride (GaN) layer with a first diamond layer having a first thermal conductivity and a second diamond layer having a second thermal conductivity twice the first thermal conductivity, the fabricating comprising:

using a microwave plasma chemical vapor deposition (CVD) process to deposit the second diamond layer of between about 2 mils to about 4 mils on the first diamond layer of less than about 1 mil.

19. The method of claim 18 wherein the fabricating further comprises using a hot filament CVD process to form the first diamond layer.

20. The method of claim 18 wherein using a microwave plasma chemical vapor deposition (CVD) process to deposit the second diamond layer on the first diamond layer comprises using a microwave plasma chemical vapor deposition (CVD) process to deposit the second diamond layer is about 4 mils.

21. The method of claim 18 wherein the fabricating further comprises:

growing the GaN layer on a first substrate;

disposing a silicon layer onto the GaN layer;

removing the first substrate;

depositing the first diamond layer onto a second substrate;

removing the second substrate;

attaching the first and second diamond layers to the GaN layer; and

removing the silicon layer.

22. The method of claim 18 wherein the fabricating further comprises:

depositing the first diamond layer on to a silicon-on-insulator (SOI) substrate;

removing an oxide from the SOI substrate; and

growing the GaN on a remaining SOI substrate.

23. The method of claim 18 wherein fabricating a gallium nitride (GaN) layer with a first diamond layer comprises disposing the first diamond layer on a first surface of the GaN and further comprising disposing a third diamond layer on a second surface of the GaN layer opposite the first surface of the GaN layer.

24. The method of claim 18 wherein fabricating a gallium nitride (GaN) layer with a first diamond layer having a first thermal conductivity and a second diamond layer having a second thermal conductivity comprises fabricating a GaN

layer comprising at least one of undoped GaN, doped GaN or GaN combined with another element.

25. The method of claim 18, further comprising fabricating at least one of a high frequency device, a high electron mobility transistor (HEMT) or a microwave device from the gallium nitride (GaN) layer with the first diamond and the second diamond layer.

26. A device, comprising:

a gallium nitride (GaN) layer;

a first layer of diamond having a first thermal conductivity disposed on the GaN layer; and

a second layer of diamond having a second thermal conductivity greater than the first thermal conductivity deposited on the first layer of diamond.

27. The device of claim 26, further comprising an interlayer disposed between the first layer of diamond and the GaN layer.

28. The device of claim 26 wherein the second diamond layer is between about 2 mils and about 4 mils and the first diamond layer is less than about 1 mil.

29. The device of claim 26 wherein the second diamond layer about 4 mils or greater and the first diamond layer is less than about 1 mil.

30. The device of claim 26 wherein the device is one of a high frequency device, a high electron mobility transistor (HEMT) or a microwave device.

31. The device of claim 26 wherein the first layer of diamond is disposed on a first surface of the GaN layer, the GaN layer further comprising a third diamond layer disposed on a second surface of the GaN layer opposite the first surface of the GaN layer.

32. The device of claim 26 wherein the GaN layer comprises at least one undoped GaN, doped GaN or GaN combined with another element.

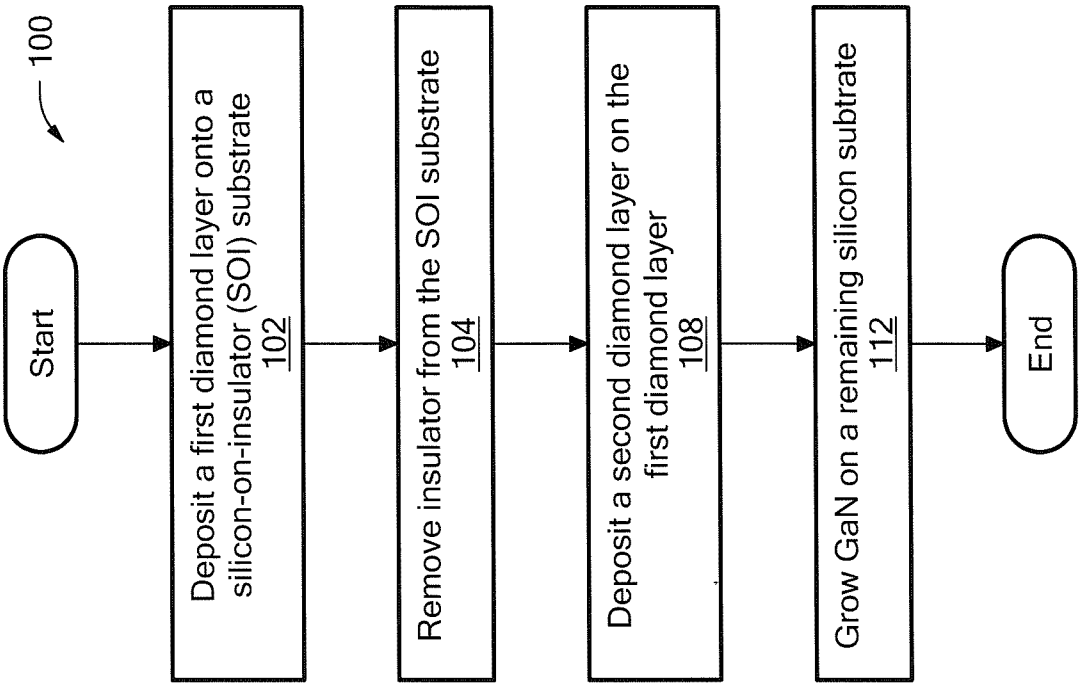


FIG. 2

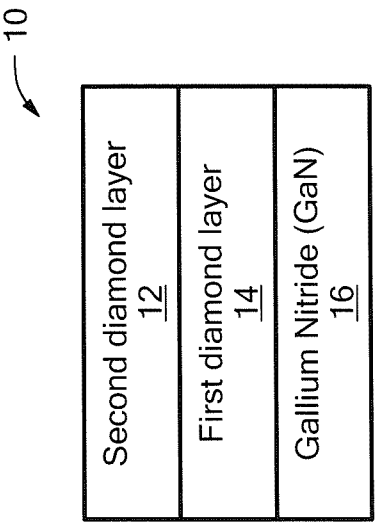


FIG. 1A



FIG. 1B

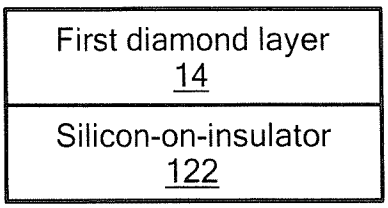


FIG. 3A

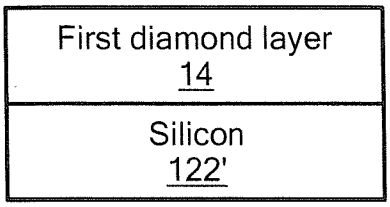


FIG. 3B

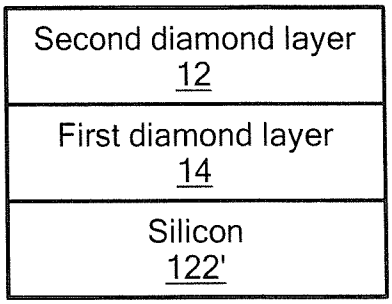


FIG. 3C

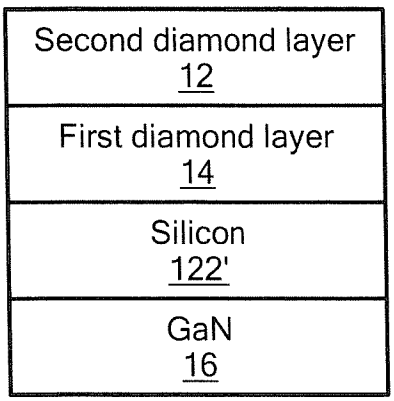


FIG. 3D

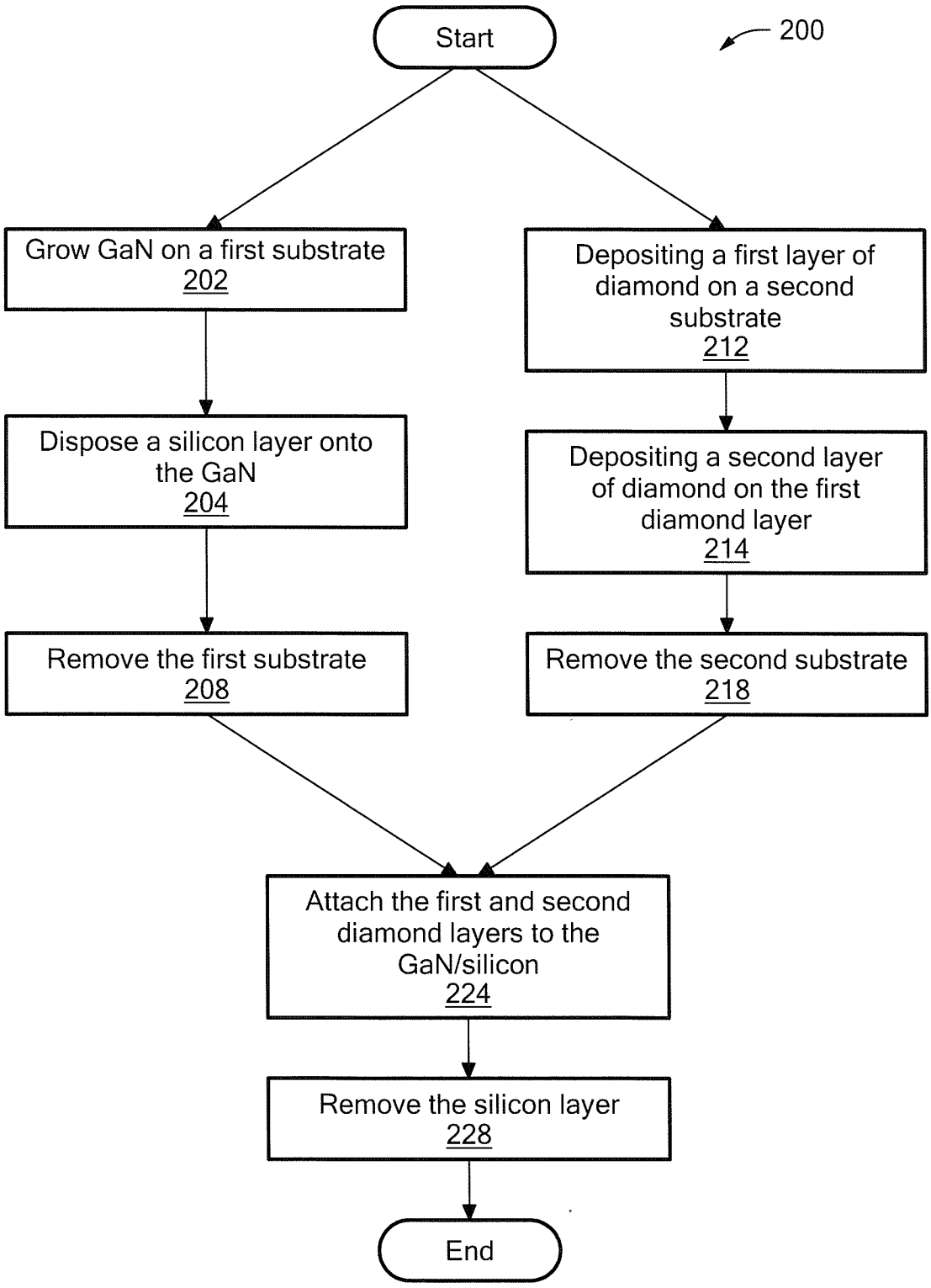

Start
200
Grow GaN on a first substrate
202
Dispose a silicon layer onto the GaN
204
Remove the first substrate
208
Depositing a first layer of diamond on a second substrate
212
Depositing a second layer of diamond on the first diamond layer
214
Remove the second substrate
218
Attach the first and second diamond layers to the GaN/silicon
224
Remove the silicon layer
228
End

FIG. 4

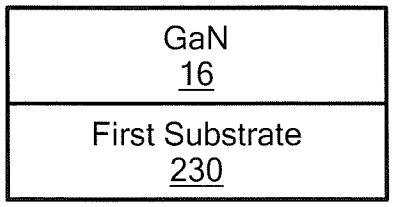


FIG. 5A

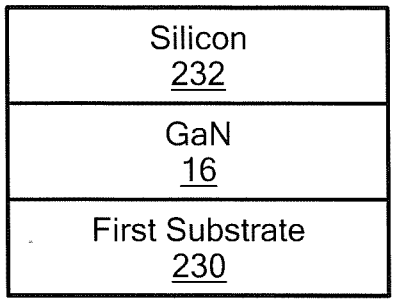


FIG. 5B

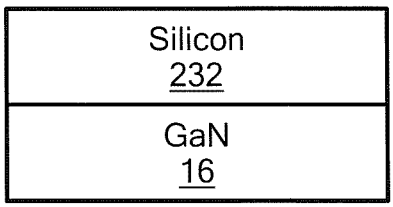


FIG. 5C

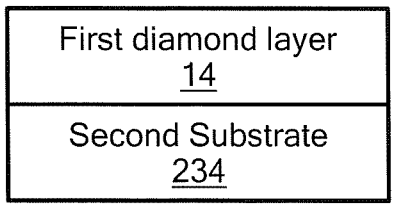


FIG. 5D

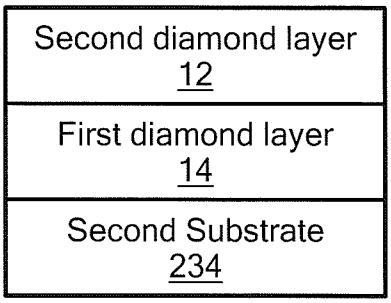


FIG. 5E

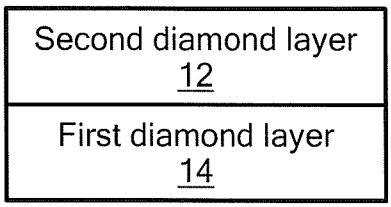


FIG. 5F

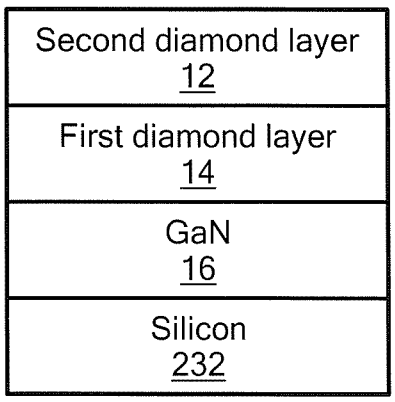


FIG. 5G

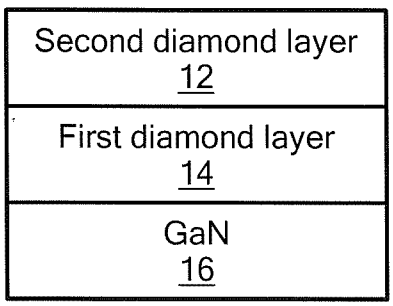


FIG. 5H

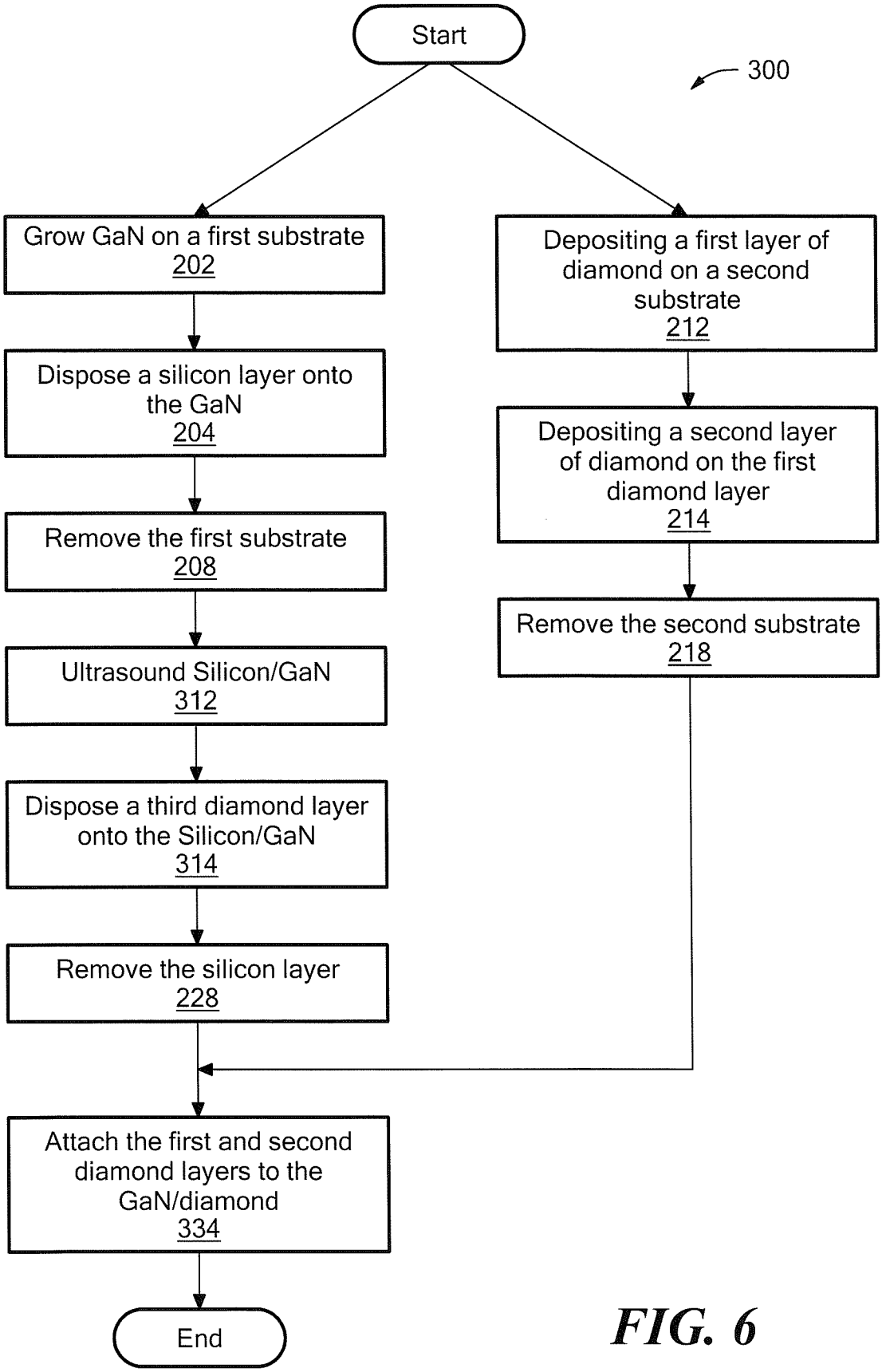

Start
300
Grow GaN on a first substrate
202
Dispose a silicon layer onto the GaN
204
Remove the first substrate
208
Ultrasound Silicon/GaN
312
Dispose a third diamond layer onto the Silicon/GaN
314
Remove the silicon layer
228
Depositing a first layer of diamond on a second substrate
212
Depositing a second layer of diamond on the first diamond layer
214
Remove the second substrate
218
Attach the first and second diamond layers to the GaN/diamond
334
End

FIG. 6

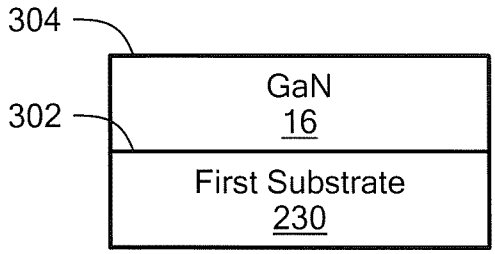


FIG. 7A

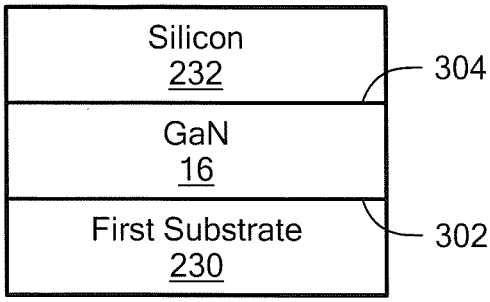


FIG. 7B

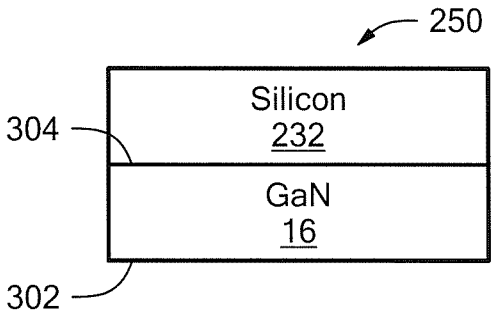


FIG. 7C

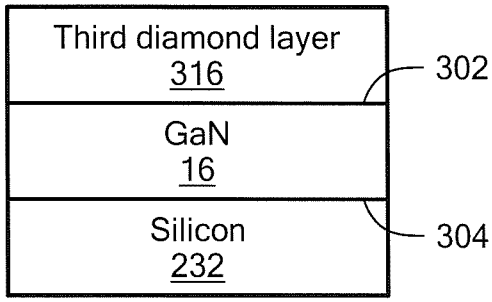


FIG. 7D

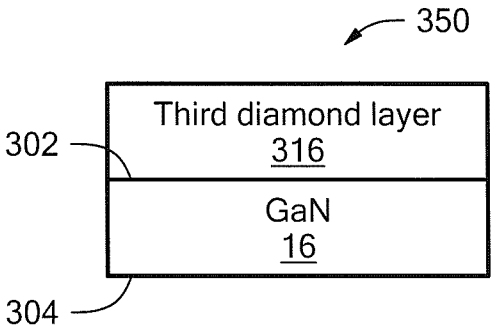


FIG. 7E

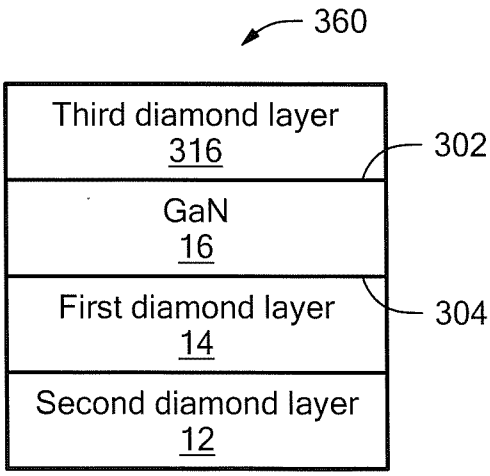


FIG. 7F

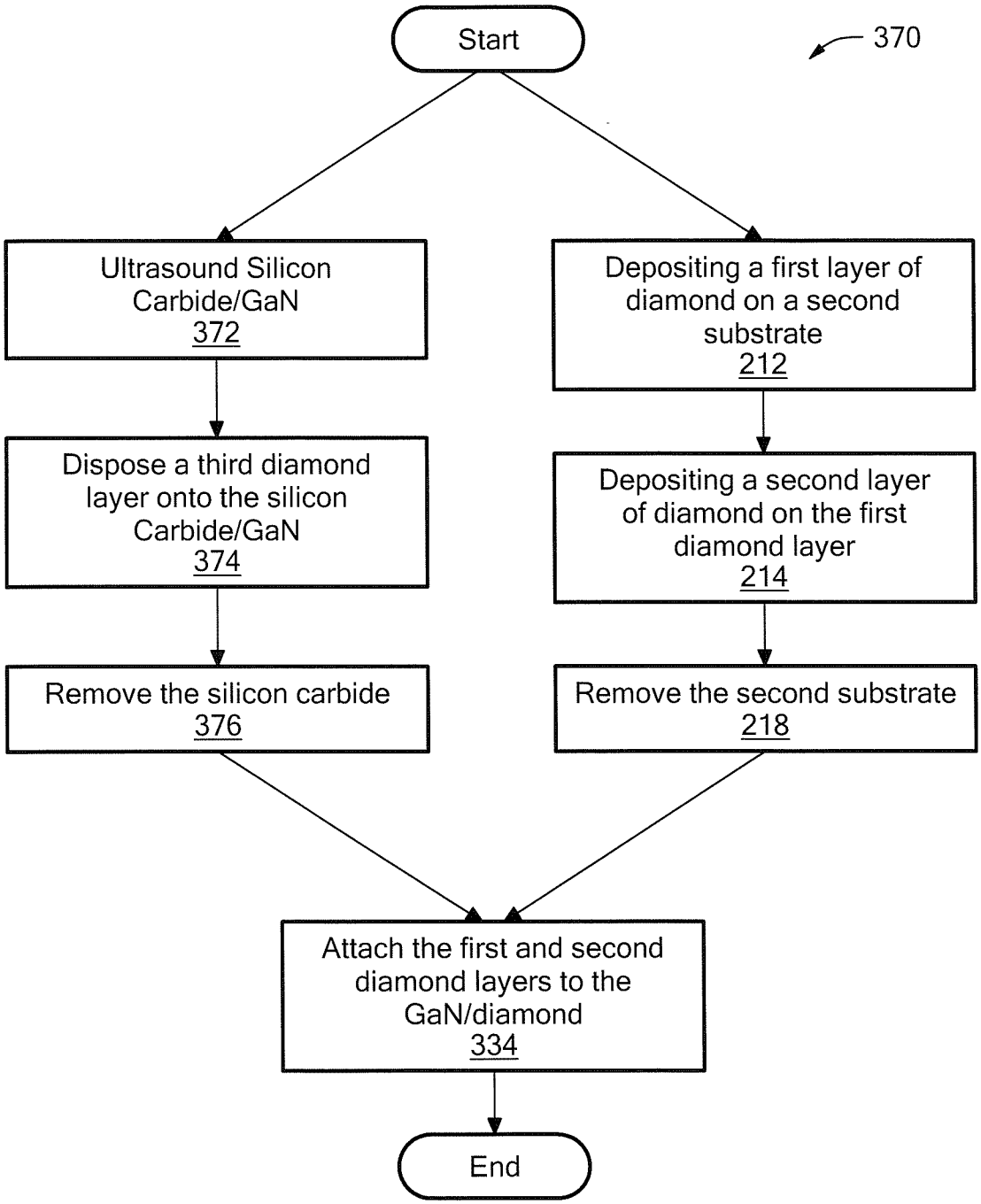

Start
370
Ultrasound Silicon Carbide/GaN
372
Dispose a third diamond layer onto the silicon Carbide/GaN
374
Remove the silicon carbide
376
Depositing a first layer of diamond on a second substrate
212
Depositing a second layer of diamond on the first diamond layer
214
Remove the second substrate
218
Attach the first and second diamond layers to the GaN/diamond
334
End

FIG. 8

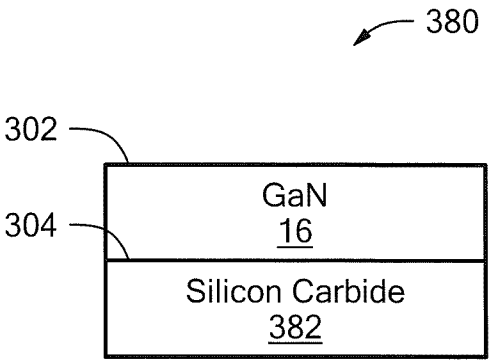


FIG. 9A

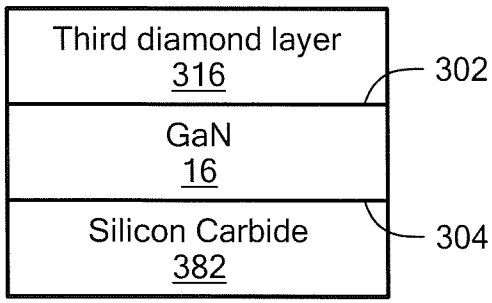


FIG. 9B

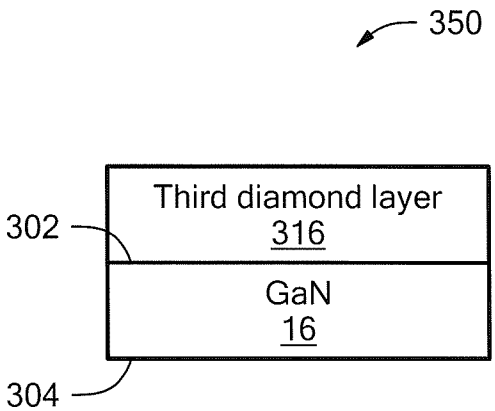


FIG. 9C

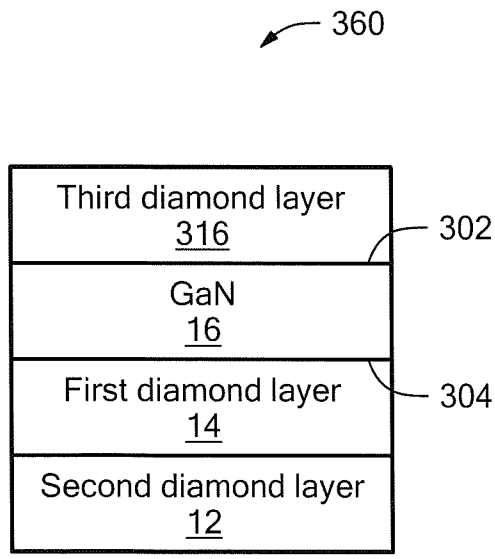


FIG. 9D

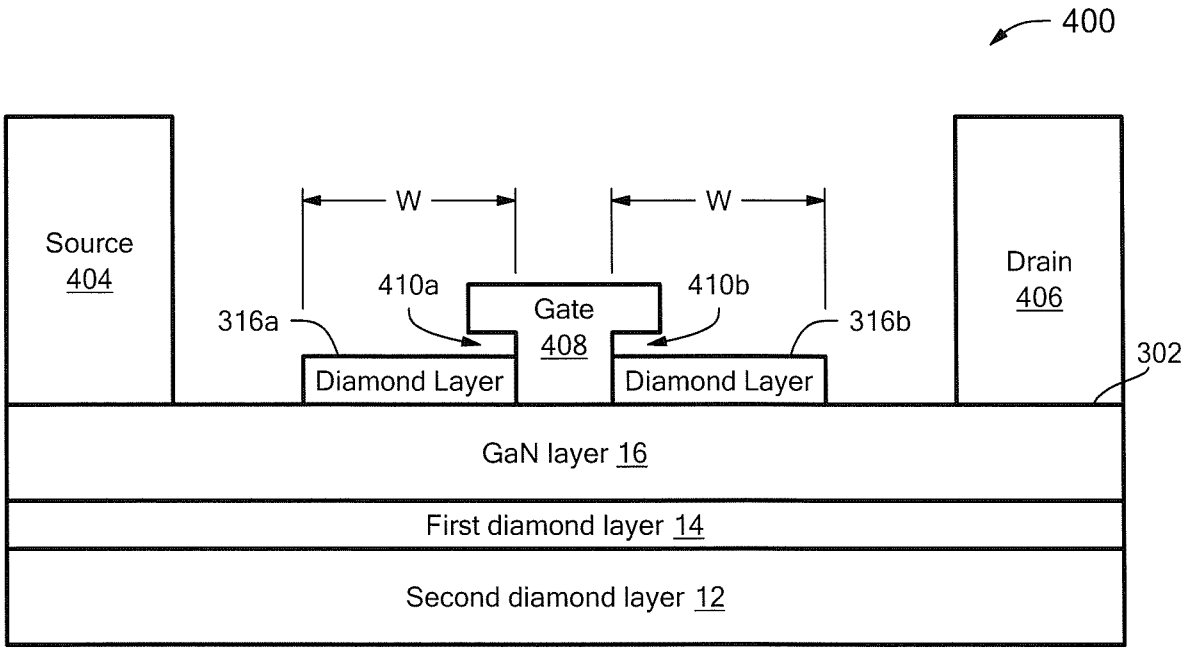

400
Source
404
W
W
Drain
406
410a
Gate
408
410b
316a
316b
302
Diamond Layer
Diamond Layer
GaN layer 16
First diamond layer 14
Second diamond layer 12

FIG. 10

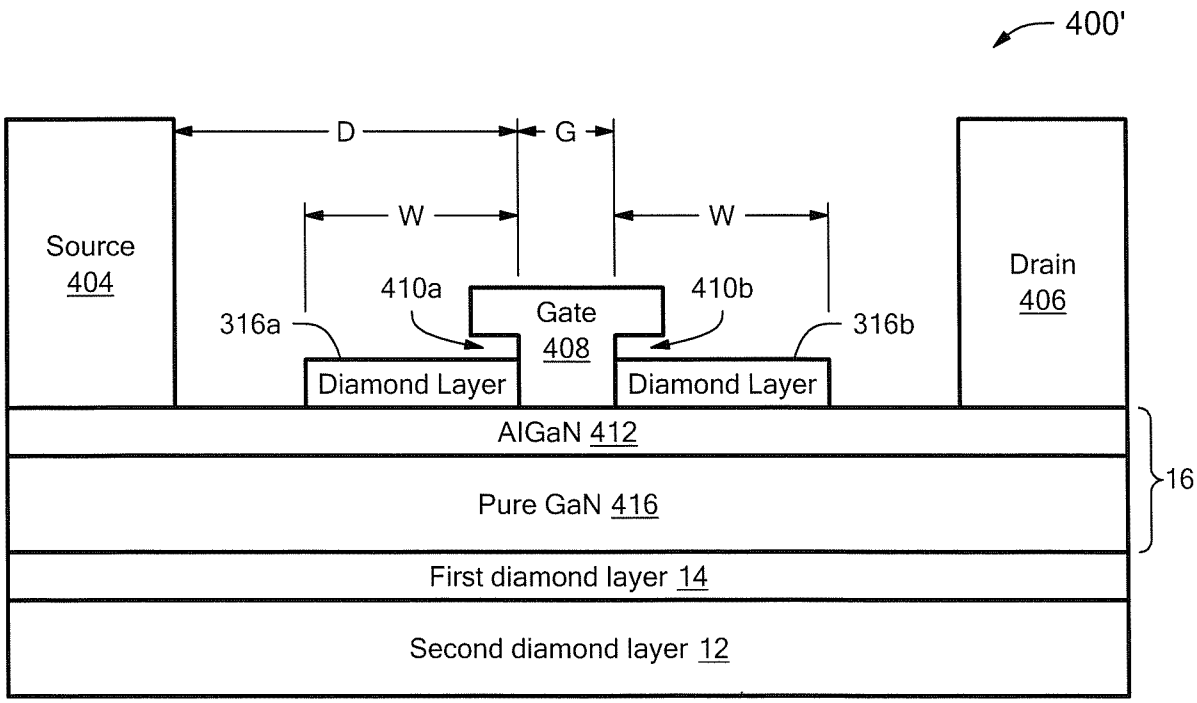

400'
D
G
W
W
Source
404
Drain
406
410a
Gate
408
410b
316a
316b
Diamond Layer
Diamond Layer
AlGaN 412
Pure GaN 416
16
First diamond layer 14
Second diamond layer 12

FIG. 11

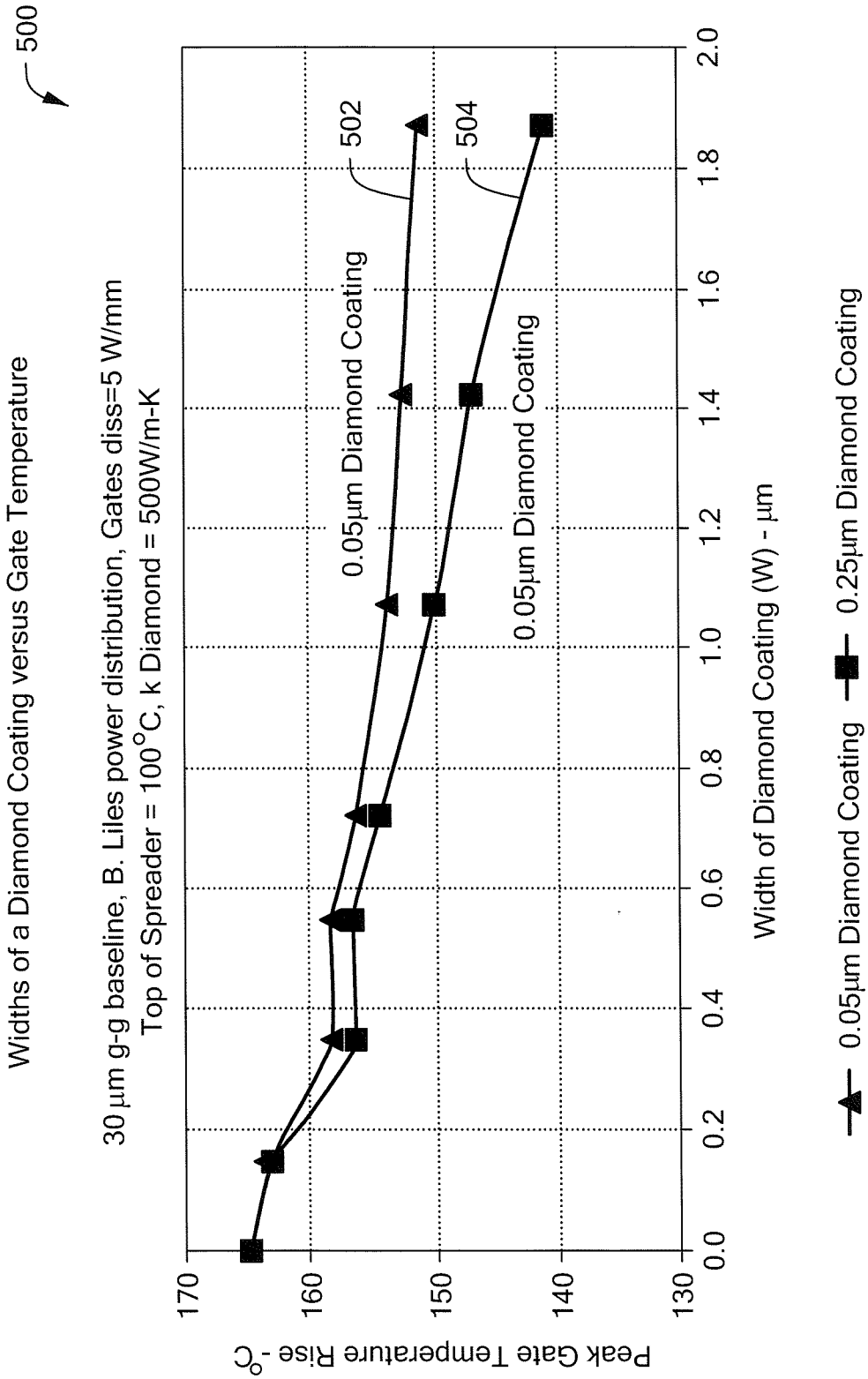

500
Widths of a Diamond Coating versus Gate Temperature
30 µm g-g baseline, B. Liles power distribution, Gates diss=5 W/mm
Top of Spreader = 100°C, k Diamond = 500W/m-K
Peak Gate Temperature Rise - °C
Width of Diamond Coating (W) - µm
502
504
0.05µm Diamond Coating
0.05µm Diamond Coating
0.05µm Diamond Coating
0.25µm Diamond Coating
170
160
150
140
130
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

FIG. 12

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2009/068178

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01L21/335 H01L29/16 H01L29/267 H01L29/778

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)
H01L

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

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 457 508 A2 (SUMITOMO ELECTRIC INDUSTRIES [JP]) 21 November 1991 (1991-11-21)	1-5, 7-14, 16-18, 20-30,32
Y	page 10, line 9 - line 39; claim 10; figure 6c	15,23,31
Y	JP 2005 210105 A (MATSUSHITA ELECTRIC IND CO LTD) 4 August 2005 (2005-08-04) paragraph [0147] - paragraph [0158]; figures 9a-9d	15,23,31
A	WO 2007/122507 A1 (BERG SOEREN [SE]; OLSSON JOERGEN [SE]; VALLIN OERJAN [SE]; SMITH ULF [) 1 November 2007 (2007-11-01) page 20, lines 30-31; claims 8,10; figures 6-7	1-32

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
8 March 2010	16/03/2010

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Fax: (+31–70) 340–3016	Franche, Vincent

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2009/068178

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2006/117621 A1 (ELEMENT SIX LTD [GB]; DONALD HEATHER JUNE [ZA]; SCARSBROOK GEOFFREY AL) 9 November 2006 (2006-11-09) page 36 - page 37; figure 3	1-32

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2009/068178

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0457508 A2	21-11-1991	DE 69127314 D1	25-09-1997
		DE 69127314 T2	18-12-1997
		JP 2961812 B2	12-10-1999
		JP 4022172 A	27-01-1992
		US 5252840 A	12-10-1993
JP 2005210105 A	04-08-2005	NONE	
WO 2007122507 A1	01-11-2007	EP 2016618 A1	21-01-2009
		US 2009173939 A1	09-07-2009
WO 2006117621 A1	09-11-2006	CN 101167190 A	23-04-2008
		EP 1875512 A1	09-01-2008
		JP 2008539575 T	13-11-2008
		KR 20080003841 A	08-01-2008
		US 2008099768 A1	01-05-2008