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(54) **Titre :** DIODES A BASE DE NITRURE DE GALLIUM A TENSION DIRECTE BASSE ET A FAIBLE COURANT INVERSE
(54) **Title:** GALLIUM NITRIDE BASED DIODES WITH LOW FORWARD VOLTAGE AND LOW REVERSE CURRENT OPERATION

(57) **Abrégé/Abstract:**
New Group III based diodes are disclosed having a low on state voltage (V_f) and structures to keep reverse current (I_{rev}) relatively low. One embodiment of the invention is Schottky barrier diode (10) made from the GaN material system in which the Fermi level

(57) Abrégé(suite)/Abstract(continued):
(or surface potential) of is not pinned. The barrier potential (33) at the metal-to-semiconductor junction varies depending on the type of metal (16) used and using particular metals lowers the diode's Schottky barrier potential (33) and results in a V_f in the range of 0.1-0.3V. In another embodiment (40) a trench structure (45) is formed on the Schottky diodes semiconductor material (44) to reduce reverse leakage current and comprises a number of parallel, equally spaced trenches (46) with mesa regions (49) between adjacent trenches (46). A third embodiment of the invention provides a GaN tunnel diode with a low Vf resulting from the tunneling of electrons through the barrier potential (81), instead of over it. An embodiment of the tunnel diode (120) can also have a trench structure (121) to reduce reverse leakage current.

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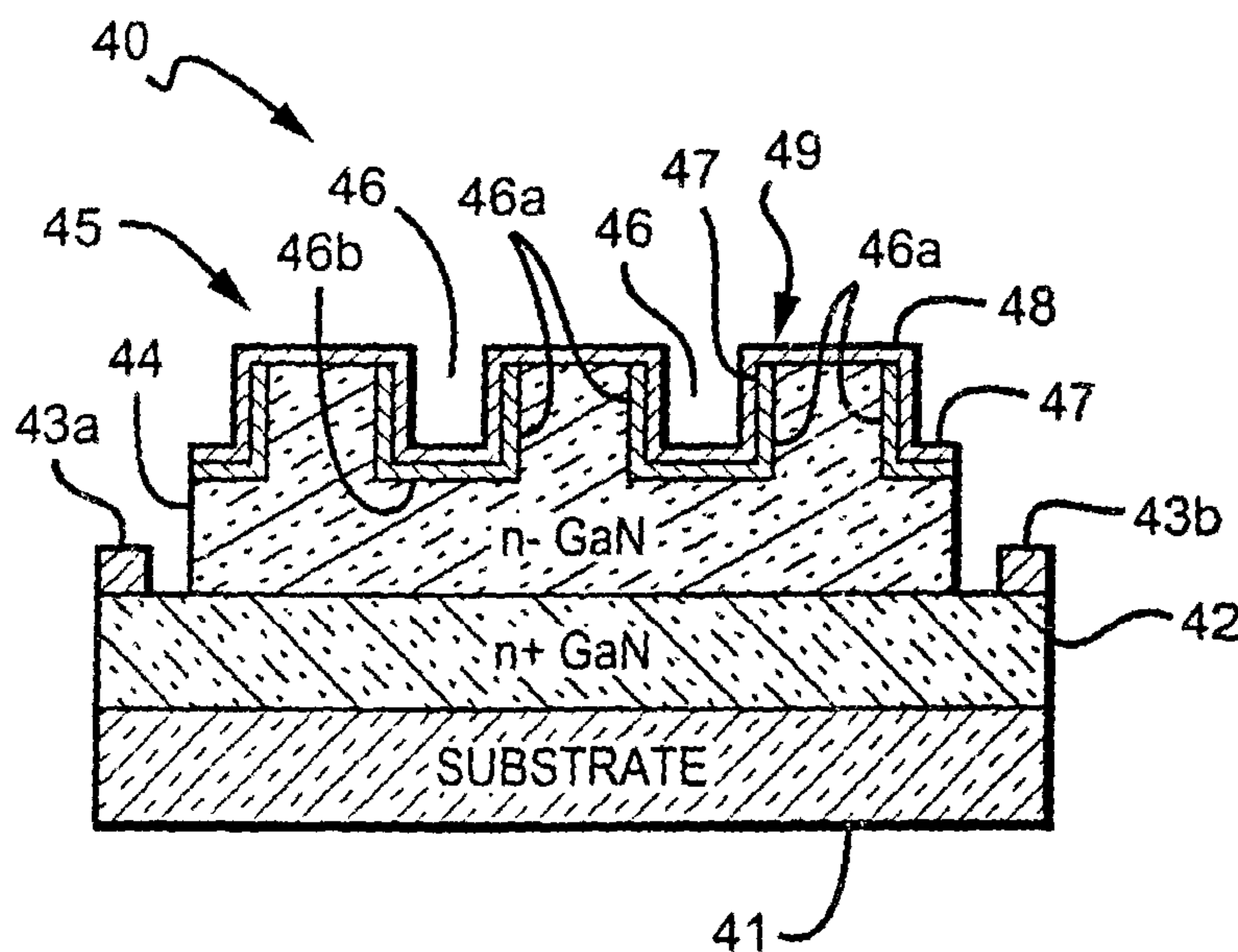
(54) **Title:** GALLIUM NITRIDE BASED DIODES WITH LOW FORWARD VOLTAGE AND LOW REVERSE CURRENT OPERATION



(57) **Abstract:** New Group III based diodes are disclosed having a low on state voltage (V_f) and structures to keep reverse current (I_{rev}) relatively low. One embodiment of the invention is Schottky barrier diode (10) made from the GaN material system in which the Fermi level (or surface potential) of is not pinned. The barrier potential (33) at the metal-to-semiconductor junction varies depending on the type of metal (16) used and using particular metals lowers the diode's Schottky barrier potential (33) and results in a V_f in the range of 0.1-0.3V. In another embodiment (40) a trench structure (45) is formed on the Schottky diodes semiconductor material (44) to reduce reverse leakage current and comprises a number of parallel, equally spaced trenches (46) with mesa regions (49) between adjacent trenches (46). A third embodiment of the invention provides a GaN tunnel diode with a low Vf resulting from the tunneling of electrons through the barrier potential (81), instead of over it. An embodiment of the tunnel diode (120) can also have a trench structure (121) to reduce reverse leakage current.

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GALLIUM NITRIDE BASED DIODES WITH LOW FORWARD VOLTAGE AND LOW REVERSE CURRENT OPERATION

5 BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to diodes, and more particularly to gallium nitride (GaN) based diodes 10 exhibiting improved forward voltage and reverse leakage current characteristics.

Description of the Related Art

Diode rectifiers are one of the most widely used 15 devices for low voltage switching, power supplies, power converters and related applications. For efficient operation it is desirable for diodes to have low on-state voltage (0.1-0.2V or lower), low reverse leakage current, high voltage blocking capability (20-30V), and high 20 switching speed.

The most common diodes are pn-junction diodes made from silicon (Si) with impurity elements introduced to modify, in a controlled manner, the diode's operating characteristics. Diodes can also be formed from other 25 semiconductor materials such as Gallium Arsenide (GaAs) and silicon carbide (SiC). One disadvantage of junction diodes is that during forward conduction the power loss in the diode can become excessive for large current flow.

Schottky barrier diodes are a special form of diode 30 rectifier that consist of a rectifying metal-to-semiconductor barrier area instead of a pn junction. When

the metal contacts the semiconductor a barrier region is developed at the junction between the two. When properly fabricated the barrier region will minimize charge storage effects and improve the diode switching by
5 shortening the turn-off time. [L.P. Hunter, Physics of Semiconductor Materials, Devices, and Circuits, Semiconductor Devices, Page 1-10 (1970)] Common Schottky diodes have a lower turn-on voltage (approximately 0.5V) than pn-junction diodes and are more desirable in
10 applications where the energy losses in the diodes can have a significant system impact (such as output rectifiers in switching power supplies).

One way to reduce the on-state voltage below 0.5V in conventional Schottky diodes is to reduce their
15 surface barrier potential. This, however, results in a trade-off of increased reverse leakage current. In addition, the reduced barrier can degrade high temperature operation and result in soft breakdown characteristics under reverse bias operation.

20 Also, Schottky diodes are commonly made of GaAs and one disadvantage of this material is that the Fermi level (or surface potential) is fixed or pinned at approximately 0.7 volts. As a result, the on-state forward voltage (V_f) is fixed. Regardless of the type of
25 metal used to contact the semiconductor, the surface potential cannot be lowered to lower the V_f.

More recently, silicon based Schottky rectifier diodes have been developed with a somewhat lower V_f. [IXYS Corporation, Si Based Power Schottky Rectifier, Part
30 Number DSS 20-0015B; International Rectifier, Si Based Shottky Rectifier, Part Number 11DQ09]. The Shottky

barrier surface potential of these devices is approximately 0.4V with the lower limit of V_f being approximately 0.3-0.4 volts. For practical purposes the lowest achievable Shottky barrier potential is around 0.4 volts with regular metalization using titanium. This results in a V_f of approximately 0.25V with a current density of 100 A/cm^2.

Other hybrid structures have been reported with a V_f of approximately 0.25V (with a barrier height of 0.58V) with operating current density of 100 A/cm^2. [M. Mehrotra, B.J. Baliga, "The Trench MOS Barrier Shottky (TMBS) Rectifier", International Electron Device Meeting, 1993]. One such design is the junction barrier controlled Schottky rectifier having a pn-junction used to tailor the electric fields to minimize reverse leakage. Another device is the trench MOS barrier rectifier in which a trench and a MOS barrier action are used to tailor the electrical field profiles. One disadvantage of this device is the introduction of a capacitance by the pn-junction. Also, pn-junctions are somewhat difficult to fabricate in Group III nitride based devices.

The Gallium nitride (GaN) material system has been used in opto-electronic devices such as high efficiency blue and green LEDs and lasers, and electronic devices such as high power microwave transistors. GaN has a 3.4eV wide direct bandgap, high electron velocity (2x10^7 cm/s), high breakdown fields (2x10^6 V/cm) and the availability of heterostructures.

SUMMARY OF THE INVENTION

The present invention provides new Group III nitride based diodes having a low V_f. Embodiments of the new diode also include structures to keep reverse current (I_{rev}) relatively low.

The new diode is preferably formed of the GaN material system, and unlike conventional diodes made from materials such as GaAs, the Fermi level (or surface potential) of GaN is not pinned at its surface states. In GaN Schottky diodes the barrier height at the metal-to-semiconductor junction varies depending on the type of metal used. Using particular metals will lower the diode's Schottky barrier height and result in a V_f in the range of 0.1-0.3V.

The new GaN Schottky diode generally includes an n+ GaN layer on a substrate, and an n- GaN layer on the n+ GaN layer opposite the substrate. Ohmic metal contacts are included on the n+ GaN layer, isolated from the n- GaN layer, and a Schottky metal layer is included on the n- GaN layer. The signal to be rectified is applied to the diode across the Schottky metal and ohmic metal contacts. When the Schottky metal is deposited on the n- GaN layer, a barrier potential forms at the surface of said n- GaN between the two. The Schottky metal layer has a work function, which determines the height of the barrier potential.

Using a metal that reduces the Schottky barrier potential results in a low V_f, but can also result in an undesirable increase in I_{rev}. A second embodiment of the present invention reduces I_{rev} by including a trench structure on the diode's surface. This structure prevents

an increase in the electric field when the new diode is under reverse bias. As a result, the Schottky barrier potential is lowered, which helps reduce I_{rev}.

The trench structure is preferably formed on the n- GaN layer, and comprises a number of parallel, equally spaced trenches with mesa regions between adjacent trenches. Each trench has an insulating layer on its sidewalls and bottom surface. A continuous Schottky metal layer is on the trench structure, covering the insulating layer and the mesas between the trenches. Alternatively, the sidewalls and bottom surface of each trench can be covered with metal instead of an insulator, with the metal electrically isolated from the Schottky metal. The mesa regions have a doping concentration and width chosen to produce the desired redistribution of electrical field under the metal-semiconductor contact.

A third embodiment of the invention provides a GaN tunnel diode with a low V_f resulting from the tunneling of electrons through the barrier potential, instead of over it. This embodiment has a substrate with an n+ GaN layer sandwiched between the substrate and an n- GaN layer. An AlGaN barrier layer is included on the n- GaN layer opposite the n+ GaN layer. An Ohmic contact is included on the n+ GaN layer and a top contact is included on the AlGaN layer. The signal to be rectified is applied across the Ohmic and top contacts.

The barrier layer design maximizes the forward tunneling probability while the different thickness and Al mole fraction of the barrier layer result in different forward and reverse operating characteristics. At a particular thickness and Al mole fraction, the diode has

a low V_f and low I_{rev}. Using a thicker barrier layer and/or increasing the Al mole concentration decreases V_f and increases I_{rev}. As the thickness or mole fraction is increased further, the new diode will assume ohmic operating characteristics, or become a conventional Schottky diode.

These and other further features and advantages of the invention would be apparent to those skilled in the art from the following detailed description, taking together with the accompanying drawings, in which:

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a sectional view of a GaN Schottky diode embodiment of the invention;

FIG. 2 is a diagram showing the work function of common metals verses their atomic number;

FIG. 3 is a band diagram for the diode shown in FIG. 1;

FIG. 4 is a sectional view of another embodiment of the GaN Schotty diode of FIG. 1, having a trench structure to reduce reverse current leakage;

FIG. 5 is a sectional view of a tunnel diode embodiment of the invention;

FIG. 6 is a band diagram for the tunnel diode of FIG 5 having a barrier layer with a thickness of 22Å and 30% Al mole fraction;

FIG. 7 is a diagram showing the voltage/current characteristics of the new tunnel diode having the band diagram of FIG. 6;

FIG. 8 is a band diagram for the tunnel diode of FIG 5 having a barrier layer with a thickness of 30Å and 30% Al mole fraction;

5 FIG. 9 is a diagram showing the voltage/current characteristics of the new tunnel diode having the band diagram of FIG. 8;

FIG. 10 is a band diagram for the tunnel diode of FIG 5 having a barrier layer with a thickness of 38Å and 30% Al mole fraction;

10 FIG. 11 is a diagram showing the voltage/current characteristics of the new tunnel diode having the band diagram of FIG. 10; and

FIG. 12 is a sectional view of a tunnel diode embodiment of the invention having a trench structure to 15 reduce reverse current leakage.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 shows a Schottky diode 10 constructed in accordance with the present invention having a reduced 20 metal-to-semiconductor barrier potential. The new diode is formed of the Group III nitride based material system or other material systems where the Fermi level is not pinned at its surface states. Group III nitrides refer to those semiconductor compounds formed between nitrogen and 25 the elements in Group III of the periodic table, usually aluminum (Al), gallium (Ga), and indium (In). The term also refers to ternary and tertiary compounds such as AlGaN and AlInGaN. The preferred materials for the new diode are GaN and AlGaN.

30 The new diode 10 comprises a substrate 11 that can be either sapphire (Al_2O_3), silicon (Si) or silicon

carbide (SiC), with the preferred substrate being a 4H polytype of silicon carbide. Other silicon carbide polytypes can also be used including 3C, 6H and 15R polytypes. An $Al_xGa_{1-x}N$ buffer layer 12 (where x in between 0 and 1) is included on the substrate 11 and provides an appropriate crystal structure transition between the silicon carbide substrate and the remainder of the diode 10.

Silicon carbide has a much closer crystal lattice match to Group III nitrides than sapphire and results in Group III nitride films of higher quality. Silicon carbide also has a very high thermal conductivity so that the total output power of Group III nitride devices on silicon carbide is not limited by the thermal dissipation of the substrate (as is the case with some devices formed on sapphire). Also, the availability of silicon carbide substrates provides the capacity for device isolation and reduced parasitic capacitance that make commercial devices possible. SiC substrates are available from Cree Research, Inc., of Durham, North Carolina and methods for producing them are set forth in the scientific literature as well as in a U.S. Patents, Nos. Re. 34,861; 4,946,547; and 5,200,022.

The new diode 10 has an n+ GaN layer 12 on a substrate 11 and an n- layer of GaN 13 on the n+ GaN layer 12, opposite the substrate 11. The n+ layer 12 is highly doped with impurities to a concentration of at least 10^{18} per centimeter cubed (cm^3), with the preferable concentration being 5 to 10 times this amount. The n-layer 13 has a lower doping concentration but is still n-type and it preferably has an impurity concentration in

the range of 5×10^{14} to 5×10^{17} per cm^3. The n-layer 13 is preferably 0.5-1 micron thick and the n+ layer 12 is 0.1 to 1.5 microns thick, although other thicknesses will also work.

5 Portions of the n- GaN layer 13 are etched down to the n+ layer and ohmic metal contacts 14a and 14b are included on the n+ GaN layer in the etched areas so that they are electrically isolated from the n- GaN layer 13. In an alternative embodiment, one or more ohmic contacts 10 can be included on the surface of the substrate that is not covered by the n+ GaN layer 12. This embodiment is particularly applicable to substrates that are n-type. A Schottky metal layer 16 is included on the n- GaN layer 13, opposite the n+ GaN layer 12.

15 The work function of a metal is the energy needed to take an electron out of the metal in a vacuum and the Fermi level of a material is the energy level at which there is a 50% probability of finding a charged carrier. A semiconductor's electron affinity is the difference 20 between its vacuum energy level and the conduction band energy level.

As described above, the surface Fermi level of GaN is unpinned and as a result, Schottky metals with different work functions result in different barrier 25 potentials. The barrier potential is approximated by the equation:

Barrier Height = work function - the semiconductor's electron affinity

30

FIG 2 is a graph 20 showing the metal work function 21 for various metal surfaces in a vacuum, verses the particular metal's atomic number 22. The metal should be chosen to provide a low Schottky barrier potential and low V_f, but high enough so that the reverse current remains low. For example, if a metal were chosen having a work function equal to the semiconductor's electron affinity, the barrier potential approaches zero. This results in a V_f that approaches zero and also increases the diode's reverse current such that the diode becomes ohmic in nature and provides no rectification.

Many different metals can be used to achieve a low barrier height, with the preferred metals including Ti(4.6 work function) 23, Cr(4.7) 24, Nb(4.3) 25, Sn(4.4) 26, W(4.6) 27 and Ta (4.3) 28. Cr 24 results in an acceptable barrier potential and is easy to deposit by conventional methods.

FIG. 3 shows a typical band diagram 30 for the new Schottky barrier diode taken on a vertical line through the diode. It shows the energy levels of Schottky metal 31, the GaN semiconductor layers 32, and the Shottky barrier potential 33.

Prior to contact of the GaN semiconductor material by the Schottky metal, the Fermi energy levels of the two are not the same. Once the contact is made and the two materials become a single thermodynamic system, a single Fermi level for the system results. This is accomplished by the flow of electrons from the semiconductor material, which has a higher Fermi level, to the Schottky metal, which has a lower Fermi level. The electrons of the semiconductor lower their energy by flowing into the

metal. This leaves the ionized donor levels of the semiconductor somewhat in excess of the number of its free electrons and the semiconductor will have a net positive charge. Electrons that have flowed from the semiconductor into the metal cause the metal have a negative electrostatic charge. The energy levels of the semiconductor are accordingly depressed, and those of the metal are raised. The presence of this surface charge of electrons and the presence of unneutralized charge ionized donor levels of the semiconductor create the dipole layer which forms the barrier potential.

In operation, the signal to be rectified by the new Schottky diode 10 is applied across the Schottky metal 14 and the ohmic contacts 14a and 14b. The rectification of the signal results from the presence of the barrier potential at the surface of the n- GaN layer 13, which inhibits the flow of charged particles within the semiconductor. When the Schottky metal 16 is positive with respect to the semiconductor (forward bias), the energy at the semiconductor side of the barrier is raised. A larger number of free electrons on the conduction band are then able to flow into the metal. The higher the semiconductor side is raised, the more electrons there are at an energy above the top of the barrier, until finally, with large bias voltages the entire distribution of free electrons in the semiconductor is able to surmount the barrier. The voltage verses current characteristics become Ohmic in nature. The lower the barrier the lower the V_f necessary to surmount the barrier.

However, as discussed above, lowering the barrier level can also increase the reverse leakage current. When the semiconductor is made positive with respect to the metal (reverse bias), the semiconductor side of the barrier is lowered relative to the metal side so that the electrons are free to flow over the top of the barrier to the semiconductor unopposed. The number of electrons present in the metal above the top of the barrier is generally very small compared to the total number of electrons in the semiconductor. The result is a very low current characteristic. When the voltage is large enough to cut-off all flow of electrons, the current will saturate. The lower the barrier potential, the smaller reverse biases needed for the current to saturate.

FIG. 4 shows another embodiment of the new GaN Schottky diode 40 that addresses the problem of increased reverse current with decreased barrier height. The diode 40 is similar to the above embodiment having a similar substrate 41, n+ GaN layer 42, and Ohmic metal contacts 43a and 43b, that can alternatively be included on the surface of the substrate. It also has an n- GaN layer 44, but instead of this layer being planar, it has a two dimensional trench structure 45 that includes trenches 46 in the n-GaN layer. The preferred trench structure 45 includes trenches 46 that are parallel and equally spaced with mesa regions 49 remaining between adjacent trenches. Each trench 46 has an insulating layer 47 covering its sidewalls 46a and bottom surface 46b. Many different insulating materials can be used with the preferred material being silicon nitride (SiN). A Schottky metal layer 48 is included over the entire trench structure 45,

sandwiching the insulating layer between the Schottky metal and the trench sidewalls and bottom surface, and covering the mesa regions 49. The mesa regions provide the direct contact area between the Schottky metal and the n- GaN layer 44. Alternatively, each trench can be covered by a metal instead of an insulator. In this embodiment, the Schottky metal should be insulated and/or separated from the trench metal.

The mesa region 49 has a doping concentration and width chosen to produce a redistribution of electrical field under the mesa's metal-semiconductor junction. This results in the peak of the diodes electrical field being pushed away from the Schottky barrier and reduced in magnitude. This reduces the barrier lowering with increased reverse bias voltage, which helps prevent reverse leakage current from increasing rapidly.

This redistribution occurs due to the coupling of the charge in the mesa 49 with the Schottky metal 48 on the top surface and with the metal on the trench sidewalls 46a and bottom surface 46b. The depletion then extends from both the top surface (as in a conventional Schottky rectifier) and the trench sidewalls 46a, depleting the conduction area from the sidewalls. The sidewall depletion reduces the electrical field under the Schottky metal layer 48 and can also be thought of as "pinching off" the reverse leakage current. The trench structure 45 keeps the reverse leakage current relatively low, even with a low barrier potentials and a low V_f.

The preferred trench structure 45 has trenches 46 that are one to two times the width of the Schottky barrier area. Accordingly, if the barrier area is 0.7 to

1.0 microns, the trench width could be in the range of 0.7 to 2 microns.

The above diodes 10 and 40 are fabricated using known techniques. Their n+ and n- GaN layers are deposited on the substrate by known deposition techniques including but not limited to metal-organic chemical vapor deposition (MOCVD). For diode 10, the n- GaN layer 13 is etched to the n+ GaN layer 12 by known etching techniques such as chemical, reactive ion etching (RIE), or ion mill etching. The Schottky and Ohmic metal layers 14, 14b and 16 are formed on the diode 10 by standard metallization techniques.

For diode 40, after the n+ and n- layers 42 and 44 are deposited on the substrate, the n- GaN layer 44 is etched by chemical or ion mill etching to form the trenches 46. The n- GaN layer 44 is further etched to the n+ GaN layer 42 for the ohmic metal 43a and 43b. The SiN insulation layer 47 is then deposited over the entire trench structure 45 and the SiN layer is etched off the mesas 49. As a final step, a continuous Schottky metal layer 48 is formed by standard metalization techniques over the trench structure 45, covering the insulation layers 47 and the exposed trench mesas 49. The ohmic metal is also formed on the n+ GaN layer 42 by standard metalization techniques. In the embodiments of the trench diode where the trenches are covered by a metal, the metal can also be deposited by standard metalization techniques.

Tunnel Diode

FIG. 5 shows another embodiment 50 of the new diode wherein V_f is low as a result of electron tunneling through the barrier region under forward bias. By tunneling through the barrier electrons do not need to cross the barrier by conventional thermionic emission over the barrier.

Like the embodiments in FIGs. 1 and 4, the new tunnel diode 50 is formed from the Group III nitride based material system and is preferably formed of GaN, AlGaN or InGaN, however other material systems will also work. Combinations of polar and non-polar materials can be used including polar on polar and polar on non-polar materials. Some examples of these materials include complex polar oxides such as strontium titanate, lithium niobate, lead zirconium titanate, and non-complex/binary oxides such as zinc oxide. The materials can be used on silicon or any silicon/dielectric stack as long as tunneling currents are allowed.

The diode 50 has a substrate 51 comprised of either sapphire, silicon carbide (SiC) or silicon Si, with SiC being the preferred substrate material for the reasons outlined above. The substrate has an n+ GaN layer 52 on it, with an n- GaN layer 53 on the n+ GaN layer 52 opposite the substrate 51. An AlGaN barrier layer 54 is included on the n- GaN layer opposite the n+ GaN template layer 52. At the edges of the diode 50, the barrier layer 54 and n- GaN layer 53 are etched down to the n+ GaN layer 52 and ohmic metal contacts 55a and 55b are included on the layer 52 in the etched areas. As with the above structures, the ohmic contacts can also be included

on the surface of the substrate. A metal contact layer 56 is included on the AlGaN barrier layer 54, opposite the n-GaN layer 53. The signal to be rectified is applied across the ohmic contacts 55a and 55b and top metal contact 56.

The AlGaN barrier layer 54 serves as a tunnel barrier. Tunneling across barriers is a quantum mechanical phenomenon and both the thickness and the Al mole fraction of the layer 54 can be varied to maximize the forward tunneling probability. The AlGaN-GaN material system a has built in piezoelectric stress, which results in piezoelectric dipoles. Generally both the piezoelectric stress and the induced charge increases with the barrier layer thickness. In the forward bias, the electrons from the piezoelectric charge enhance tunneling since they are available for conduction so that the number of states from which tunneling can occur is increased. Accordingly the new tunnel diode can be made of other polar material exhibiting this type of piezoelectric charge.

However, under a reverse bias the piezoelectric charge also allows an increase in the reverse leakage current. The thicker the barrier layer or increased Al mole fraction, results in a lower V_f but also results in an increased I_{rev}. Accordingly, there is an optimum barrier layer thickness for a particular Al mole fraction of the barrier layer to achieve operating characteristics of low V_f and relatively low I_{rev}.

FIGs 6-11 illustrate the new diode's rectification characteristics for three different thicknesses of an AlGaN barrier layer with 30% Al. For each thickness there

is a band energy diagram and a corresponding voltage vs. current graph.

FIG. 6 shows the band diagram 60 for the tunnel diode 50 having 22Å thick barrier layer 54. It shows a typical barrier potential 61 at the junction between the barrier layer 63 and the n- GaN semiconductor layer 62. The top contact metal 64 is on the barrier layer 63, opposite the semiconductor layer. FIG. 7 shows a graph 70 plotting the corresponding current vs. voltage characteristics of the diode in FIG. 6. It has a V_f 71 of approximately 0.1V and low reverse current (I_{rev}) 72.

FIG. 8 shows a band diagram 80 for the same tunnel diode with a 30Å thick barrier layer. The increase in the barrier layer thickness increases the barrier region's piezoelectric charge, thereby enhancing tunneling across the barrier. This flattens the barrier potential 81 at the junction between the barrier layer 82 and the n-GaN layer 83. Charges do not need to overcome the barrier when a forward bias is applied, greatly reducing the diode's V_f. However, the flattened barrier also allows for increase reverse leakage current (I_{rev}). FIG. 9 is a graph 90 showing the V_f 91 that is lower than the V_f in FIG. 7. Also, I_{rev} 92 is increased compared to I_{rev} in FIG. 7.

FIG. 10 shows a band diagram 100 for the same tunnel diode with a 38Å thick barrier layer. Again, the increase in the barrier layer thickness increases the piezoelectric charge. At this thickness, the barrier potential 101 between the barrier layer 102 and n- GaN layer tails down near the junction between the barrier layer and n- GaN layer, which results in there being no barrier to charges in both forward and reverse bias. FIG.

11 shows a graph 110 of the corresponding current vs. voltage characteristics. The diode 100 experiences immediate forward and reverse current in response to forward and reverse bias such that the diode becomes ohmic in nature.

In the case where the mole concentration of aluminum in the barrier layer is different, the thicknesses of the layers would be different to achieve the characteristics shown in FIGs. 6 through 11.

FIG. 12 shows the new tunneling diode 120 with a trench structure 121 to reduce reverse current. Like the Schottky diode 40 above, the trench structure includes a number of parallel, equally spaced trenches 122, but in this diode, they are etched through the AlGaN barrier layer 123 and the n- GaN layer 124, to the n+ GaN layer 125 (AP GaN Template). There are mesa regions 126 between adjacent trenches 122. The trench sidewalls and bottom surface have an insulation layer 127 with the top Schottky metal layer 128 covering the entire trench structure 121. The trench structure functions in the same way as the embodiment above, reducing the reverse current. This is useful for the tunnel diodes having barrier layers of a thickness that results in immediate forward current in response to forward voltage. By using trench structures, the diode could also have improved reverse current leakage. Also like above, the trench sidewalls and bottom surface can be covered by a metal as long as it is isolated from the Schottky metal layer 128.

Although the present invention has been described in considerable detail with reference to certain preferred configurations thereof, other versions are possible.

The scope of the claims should not be limited by the preferred embodiments set forth in the examples, but should be given the broadest interpretation consistent with the description as a whole.

5 WE CLAIM:

1. A group III nitride based diode, comprising:
an n+ doped GaN layer (42);
an n- doped GaN layer (44) on said n+ doped GaN layer (42);
10 a Schottky metal layer (48) on said n- doped GaN layer (44) having a work function, said n- doped GaN layer (44) forming a junction with said Schottky metal layer (48), said junction having a barrier potential energy level (33) that is dependent upon the work function of said Schottky metal layer (48); and
a trench structure (45) on the surface of said n- doped GaN layer (44), said trench
15 structure (45) comprising a plurality of trenches (46) coated by a layer of metal (47) having a high work function,
wherein said trench structure comprises mesa regions (49) between adjacent trenches of said plurality of trenches (46), said trenches (46) having sidewalls (46a) and a bottom surface (46b) coated by a layer of metal (47) having a high work function, said
20 Schottky metal layer (48) covering said trenches (46) and mesa regions (49), said layer of metal (47) sandwiched between said Schottky metal layer (48) and said sidewalls (46a) and bottom surfaces (46b).

2. The diode of claim 1, wherein said barrier potential energy level (33) depends on
25 said Schottky metal work function.

3. The diode of claim 1, wherein said n- doped GaN layer (44) has an electron affinity, said barrier potential energy level (33) being approximately equal to said Schottky metal work function minus said electron affinity.

30

4. The diode of claim 1, further comprising a substrate (41) adjacent to said n+ doped GaN layer (42), opposite said n- doped GaN layer (44).

5. The diode of claim 4, wherein said substrate (41) is sapphire (Al_2O_3), silicon
35 carbide (SiC) or silicon (Si).

5 6. The diode of claim 1, wherein said Schottky metal layer (48) is one of the metals from the group comprising Ti, Cr, Nb, Sn, W and Ta.

7. The diode of claim 1, wherein said n+ doped GaN layer (42) is doped with impurities to a concentration of at least 10^{18} per centimeter cubed (cm^3).

10

8. The diode of claim 1, wherein said n- doped GaN layer (44) is doped with impurities to a concentration in the range of 5 X 10^{14} to 5 X 10^{17} per cm^3.

9. The diode of claim 1, wherein said plurality of trenches (46) are parallel and
15 equally spaced.

10. The diode of claim 1, further comprising an ohmic contact (43a, 43b) on said n+ GaN doped layer (42), a signal applied to said diode across said ohmic contact (43a, 43b) and said Schottky metal layer (48).

20

11. A diode, comprising:

a layer of highly doped gallium nitride semiconductor material (42);

a layer of lower doped gallium nitride semiconductor material (44) adjacent to the highly doped gallium nitride semiconductor material (42), said lower doped gallium
25 nitride semiconductor layer having an unpinned surface potential;

a Schottky metal layer (48) on said lower doped gallium nitride semiconductor material (44), said lower doped gallium nitride semiconductor material (44) forming a junction with said Schottky metal layer (48) having a barrier potential energy level (33) that is dependent upon the type of Schottky metal (48), with said barrier potential energy
30 level being of a magnitude that allows said diode to operate as a low forward voltage diode, said diode experiencing a reverse leakage current under reverse bias; and

a means for reducing the amount of said reverse leakage current, said means comprising a trench structure (45) on the surface of said layer of lower doped gallium nitride semiconductor material (44), said trench structure (45) comprising a plurality of
35 trenches (46) coated by a layer of metal (47) having a high work function,

wherein said trench structure comprises mesa regions (49) between adjacent trenches of said plurality of trenches (46), said trenches (46) having sidewalls (46a) and a

5 bottom surface (46b) coated by a layer of metal (47) having a high work function, said Schottky metal layer (48) covering said trenches (46) and mesa regions (49), said layer of metal (47) sandwiched between said Schottky metal layer (48) and said sidewalls (46a) and bottom surfaces (46b).

10 12. The diode of claim 11, wherein said highly doped gallium nitride semiconductor material and said lower doped gallium nitride semiconductor material are both doped n type.

13. The diode of claim 11, wherein said highly doped gallium nitride semiconductor 15 material and said lower doped gallium nitride semiconductor material comprises a group III nitride.

14. The diode of claim 11, wherein said highly doped gallium nitride semiconductor material (42) is n+ doped and said lower doped gallium nitride semiconductor material 20 (44) is n- doped.

15. The diode of claim 11, wherein said Schottky metal layer (48) has a work function, said barrier potential energy level (33) having an energy level that varies depending on said work function of said Schottky metal (48).

25

16. The diode of claim 11, further comprising a substrate (41) adjacent to said highly doped layer (42), opposite said lower doped layer (44).

17. The diode of claim 16, wherein said substrate (41) is sapphire (Al_2O_3), silicon 30 carbide (SiC) or silicon (Si).

18. The diode of claim 11, wherein said Schottky metal layer (48) is one of the metals in the group comprising Ti, Cr, Nb, Sn, W and Ta.

35 19. The diode of claim 14, wherein said n+ doped GaN layer (42) is doped with impurities to a concentration of at least 10^{18} per centimeter cubed (cm^3).

5 20. The diode of claim 14, wherein the n- doped GaN layer (44) is doped with impurities to a concentration in the range of 5×10^{14} to 5×10^{17} per cm^3.

21. The diode of claim 11, further comprising an ohmic contact (43a, 43b) on said highly doped gallium nitride semiconductor material.

10

22. A Schottky diode, comprising

a layer of highly doped Group III nitride semiconductor material (42);

a layer of lower doped Group III nitride semiconductor material (44) on said layer of highly doped Group III nitride semiconductor material, said lower doped Group III

15 nitride semiconductor material having an unpinned surface potential;

a Schottky metal (48) having a work function and forming a junction with said lower doped Group III nitride semiconductor material (44) that has a barrier potential energy level (33), said barrier potential energy level (33) depending upon said work function; and

20 a trench structure (45) in said layer of lower doped Group III nitride semiconductor material (44) said trench structure comprising a plurality of trenches (46) coated by a layer of metal (47) having a high work function,

wherein said trench structure comprises mesa regions (49) between adjacent trenches of said plurality of trenches (46), said trenches (46) having sidewalls (46a) and a

25 bottom surface (46b) coated by a layer of metal (47) having a high work function, said Schottky metal layer (48) covering said trenches (46) and mesa regions (49), said layer of metal (47) sandwiched between said Schottky metal layer (48) and said sidewalls (46a) and bottom surfaces (46b).

30 23. The diode of claim 22, wherein said highly doped Group III nitride semiconductor material (42) comprises an n+ doped GaN (42) layer and said lower doped Group III nitride semiconductor material (44) comprises an n- doped GaN layer (44).

24. The diode of claim 23, further comprising an ohmic contact (43a, 43b) on said n+

35 doped GaN layer (42).

5 25. The diode of claim 23, wherein said barrier potential energy level (33) varies positively with the work function of said Schottky metal (48).

26. The diode of claim 23, further comprising a substrate (41) made of sapphire (Al_2O_3), silicon carbide (SiC) or silicon (Si), adjacent to said n+ doped GaN layer,
10 opposite said n- doped GaN layer.

27. The diode of claim 22, wherein said Schottky metal (48) is one of the metals in the group comprising Ti, Cr, Nb, Sn, W, Ta, Ge and other metals with similar work functions.

15 28. The diode of claim 22, said diode experiencing a reverse leakage current under reverse bias, said trench structure (45) reducing said reverse leakage current.

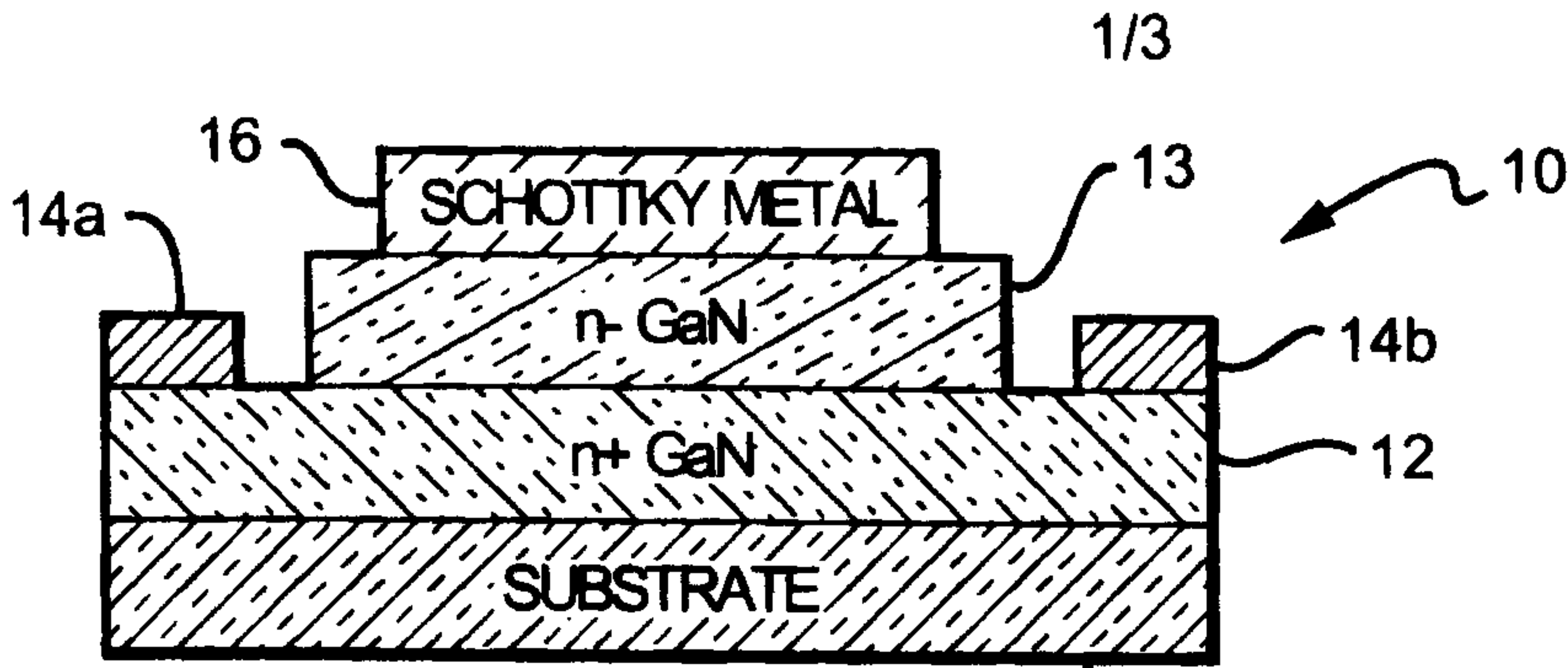
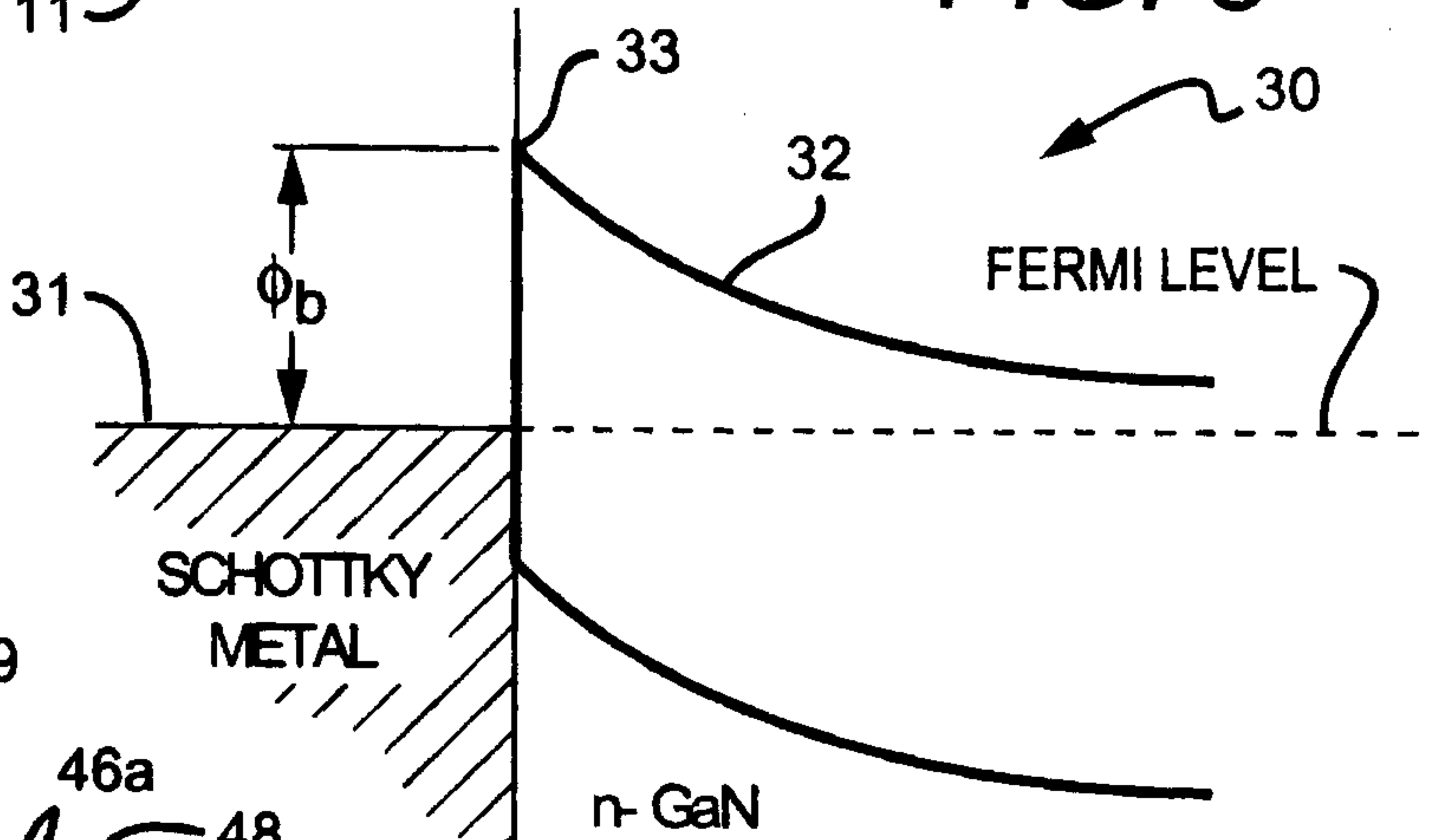


FIG. 1

FIG. 3



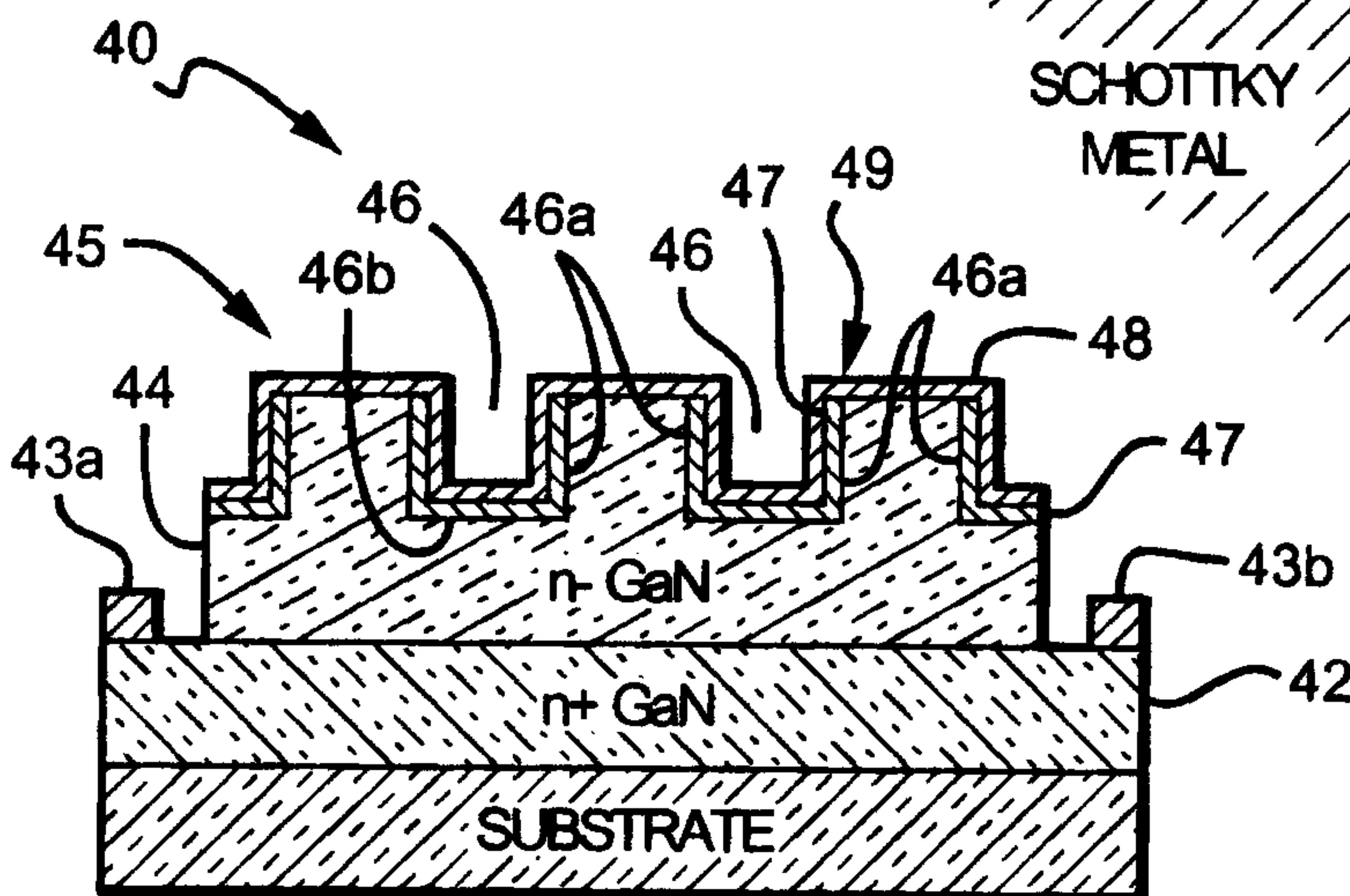


FIG. 4

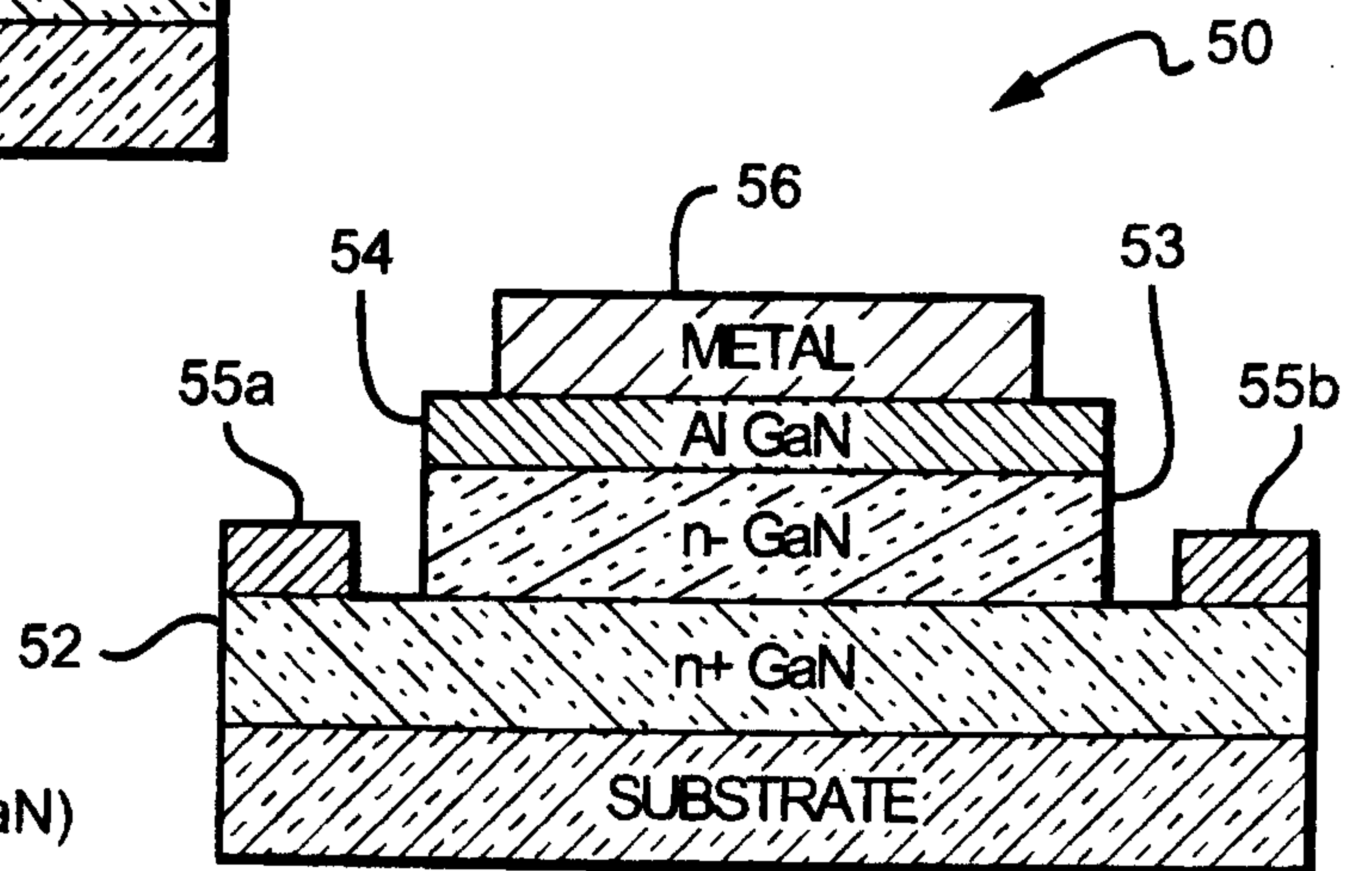


FIG. 5

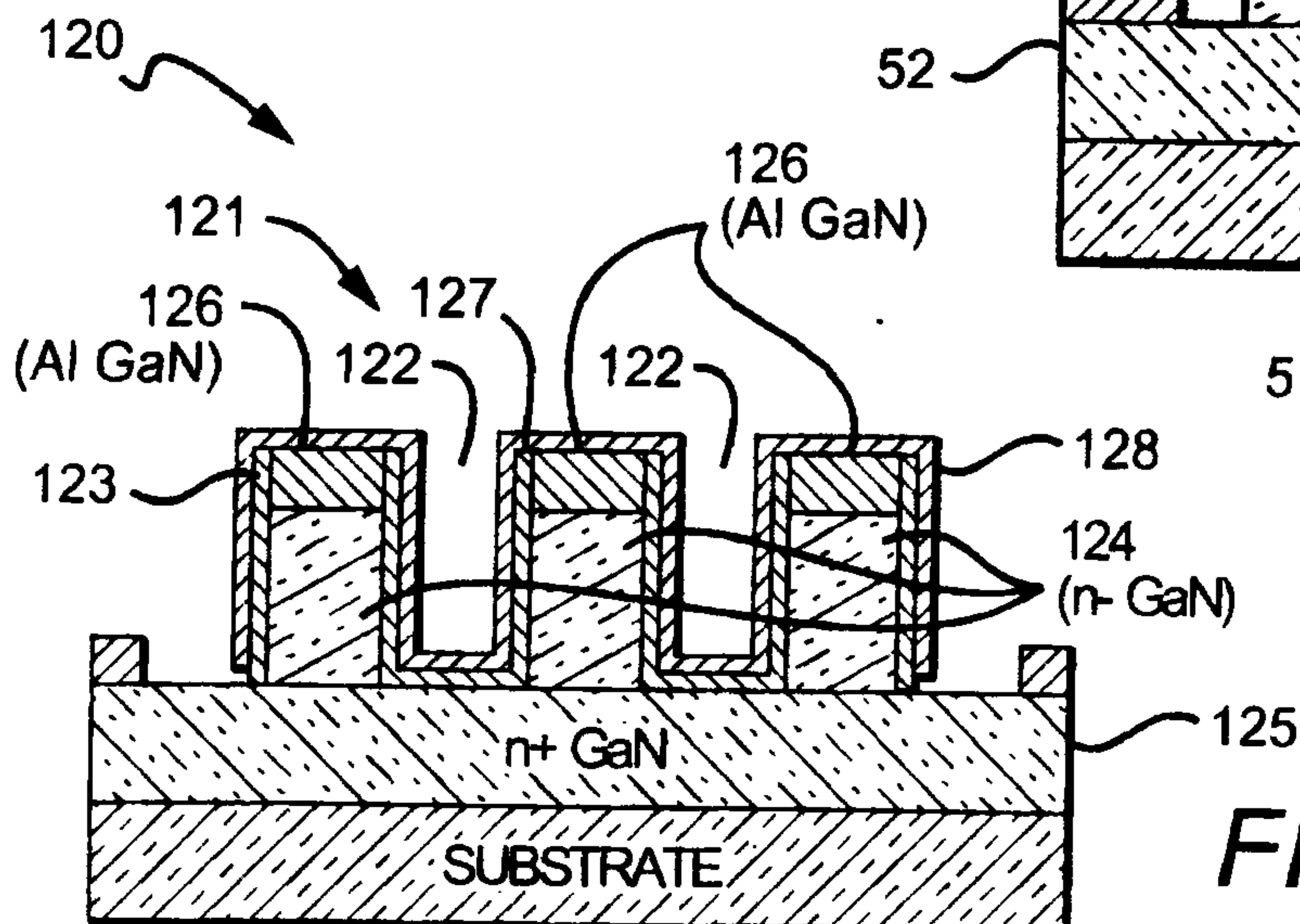


FIG. 12

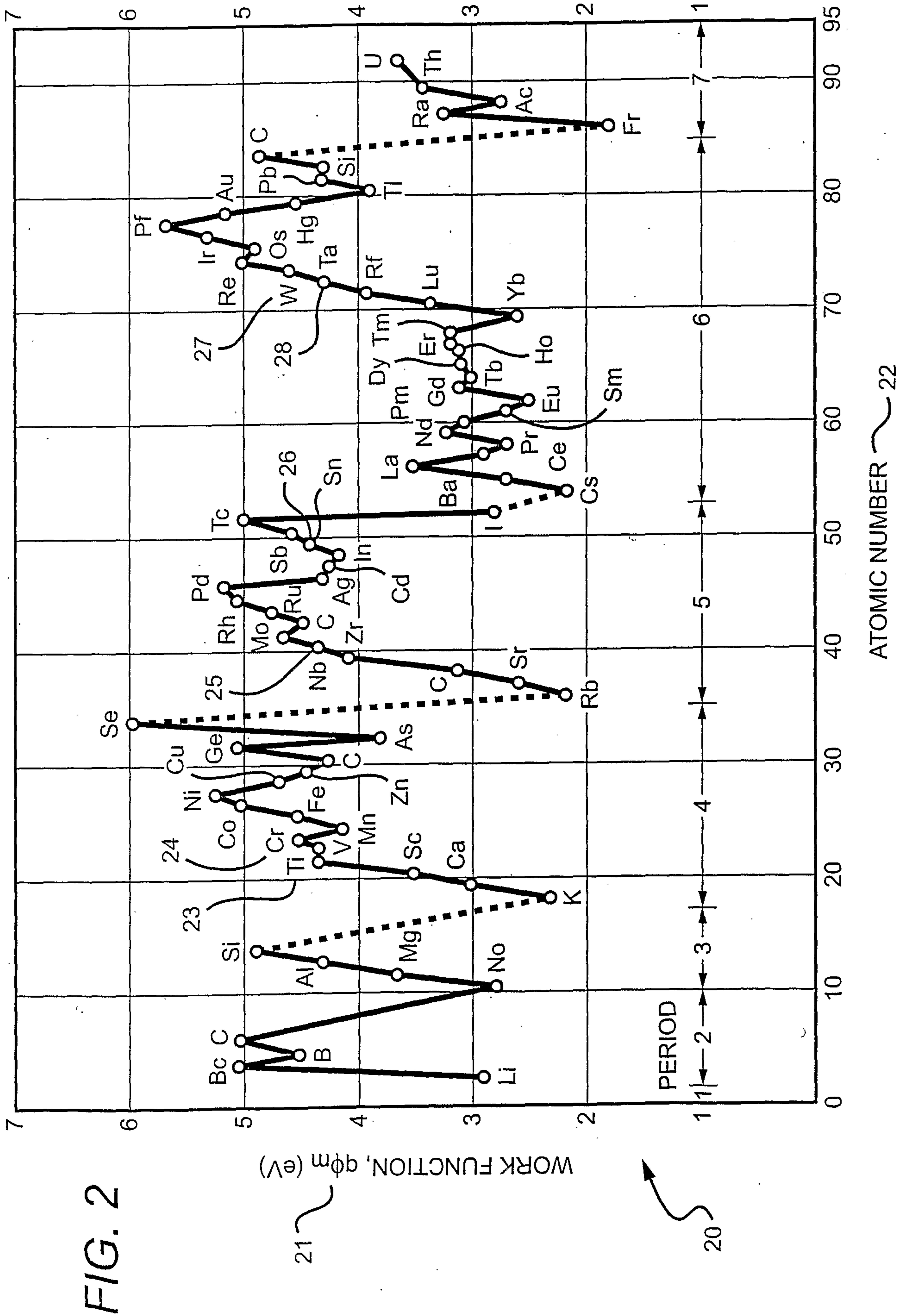


FIG. 2
WORK FUNCTION, qφm (eV)
ATOMIC NUMBER
PERIOD
20
21
22
23
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27
28

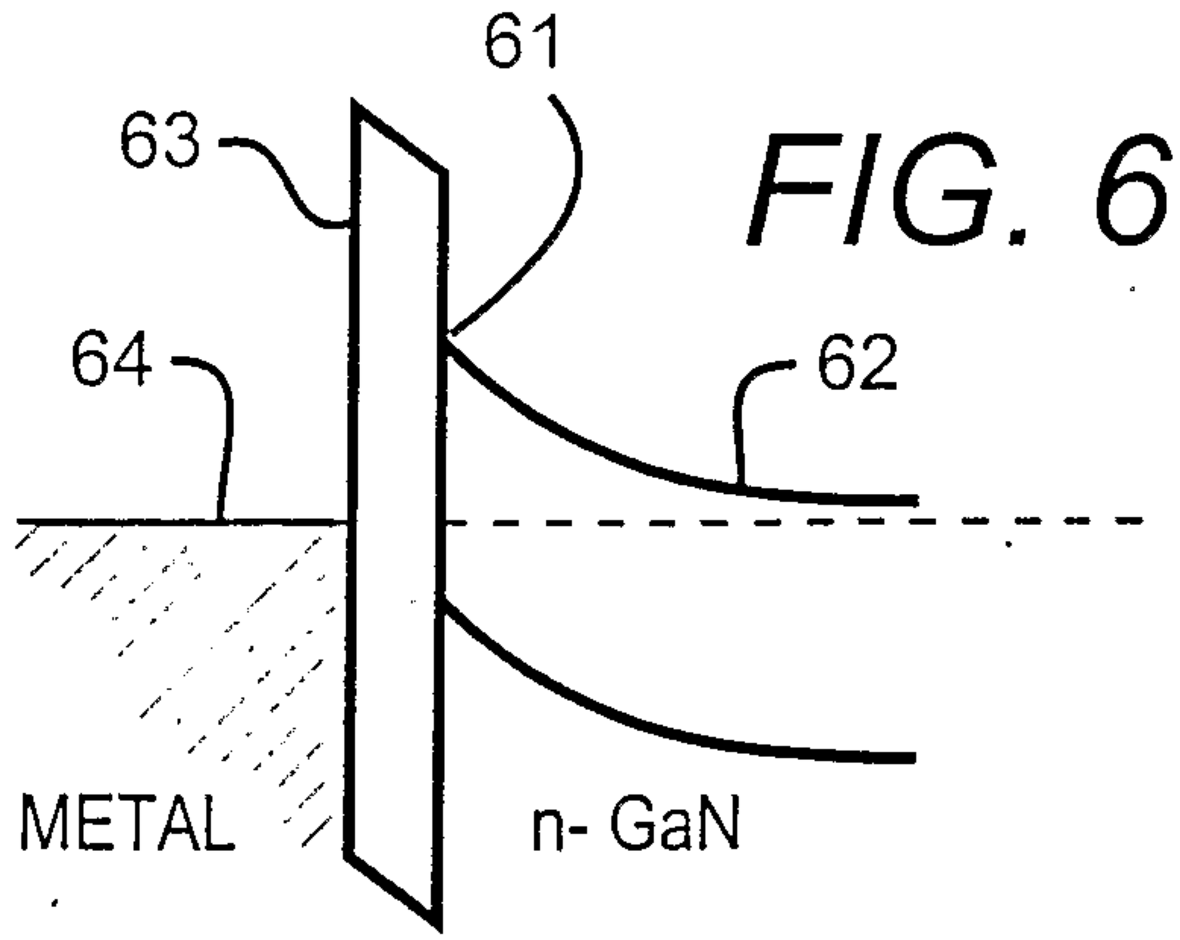


FIG. 6

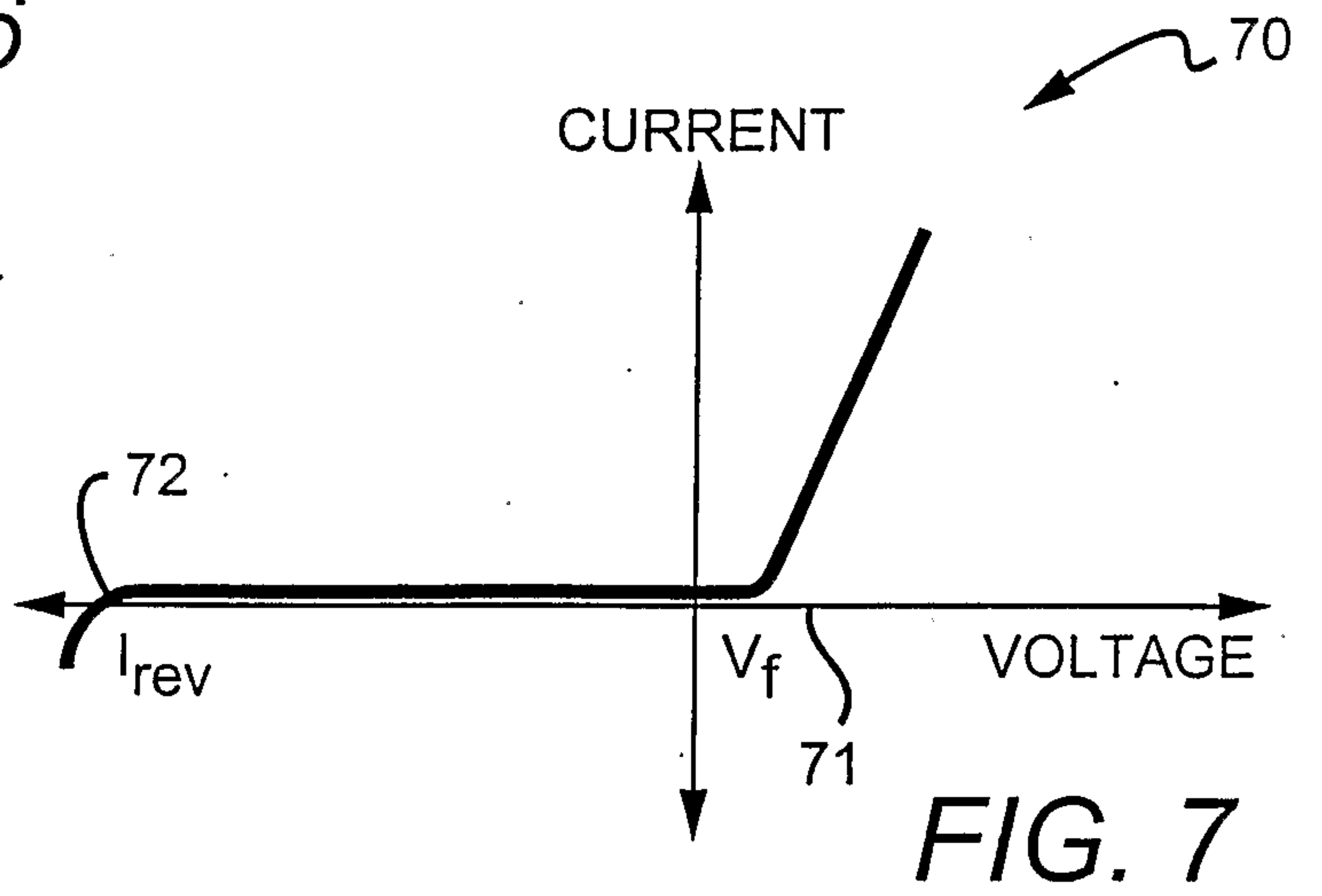


FIG. 7

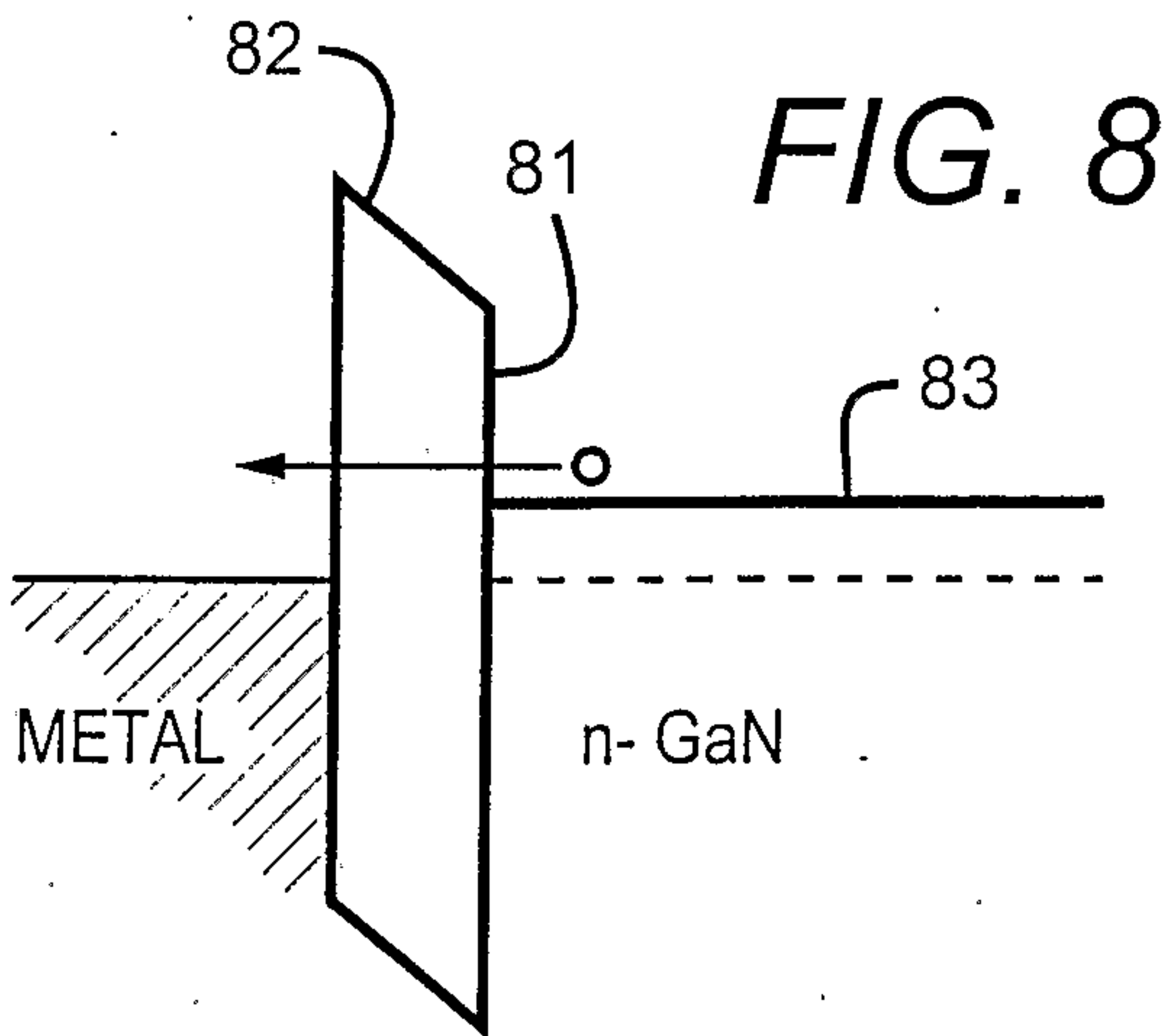


FIG. 8

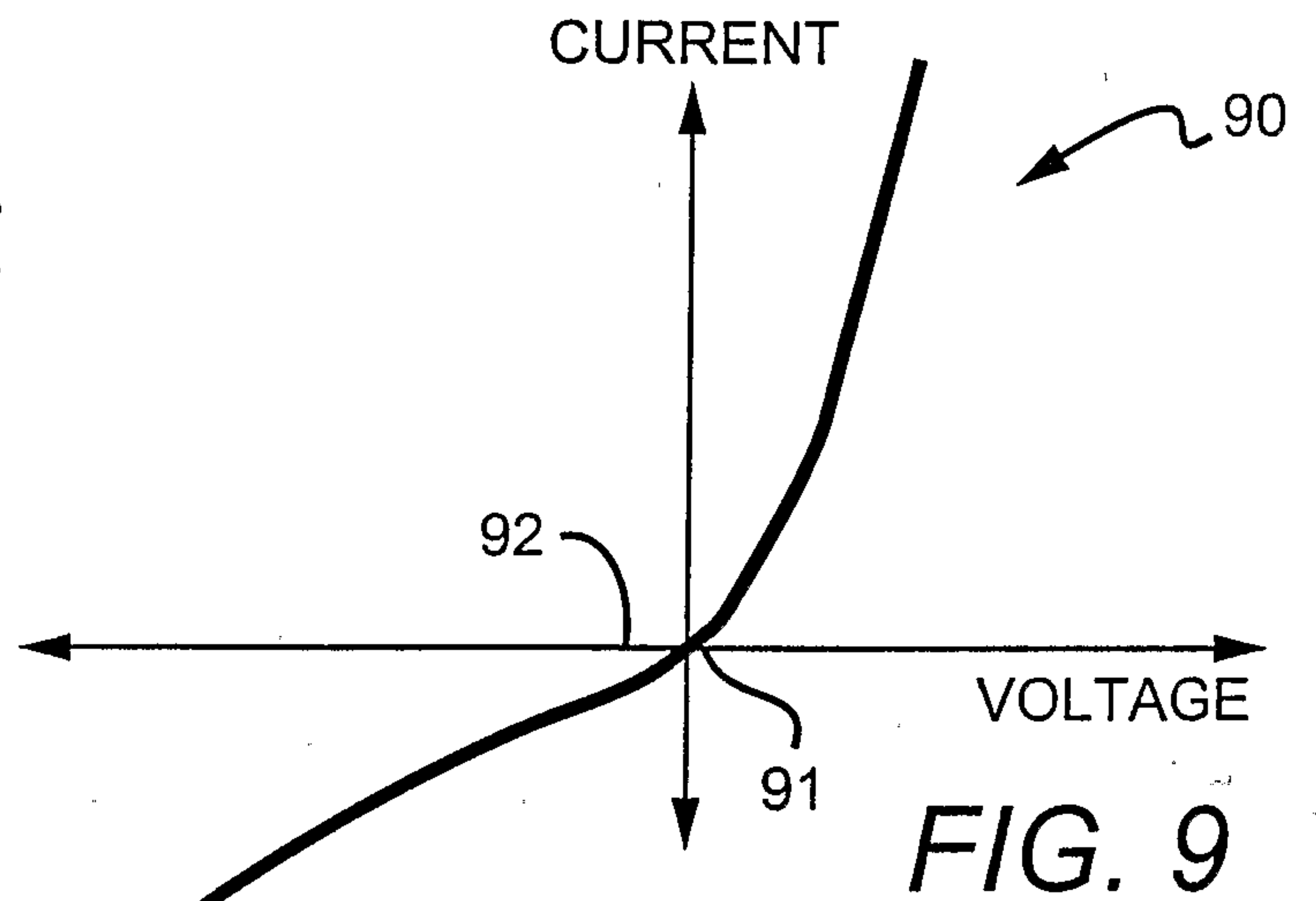


FIG. 9

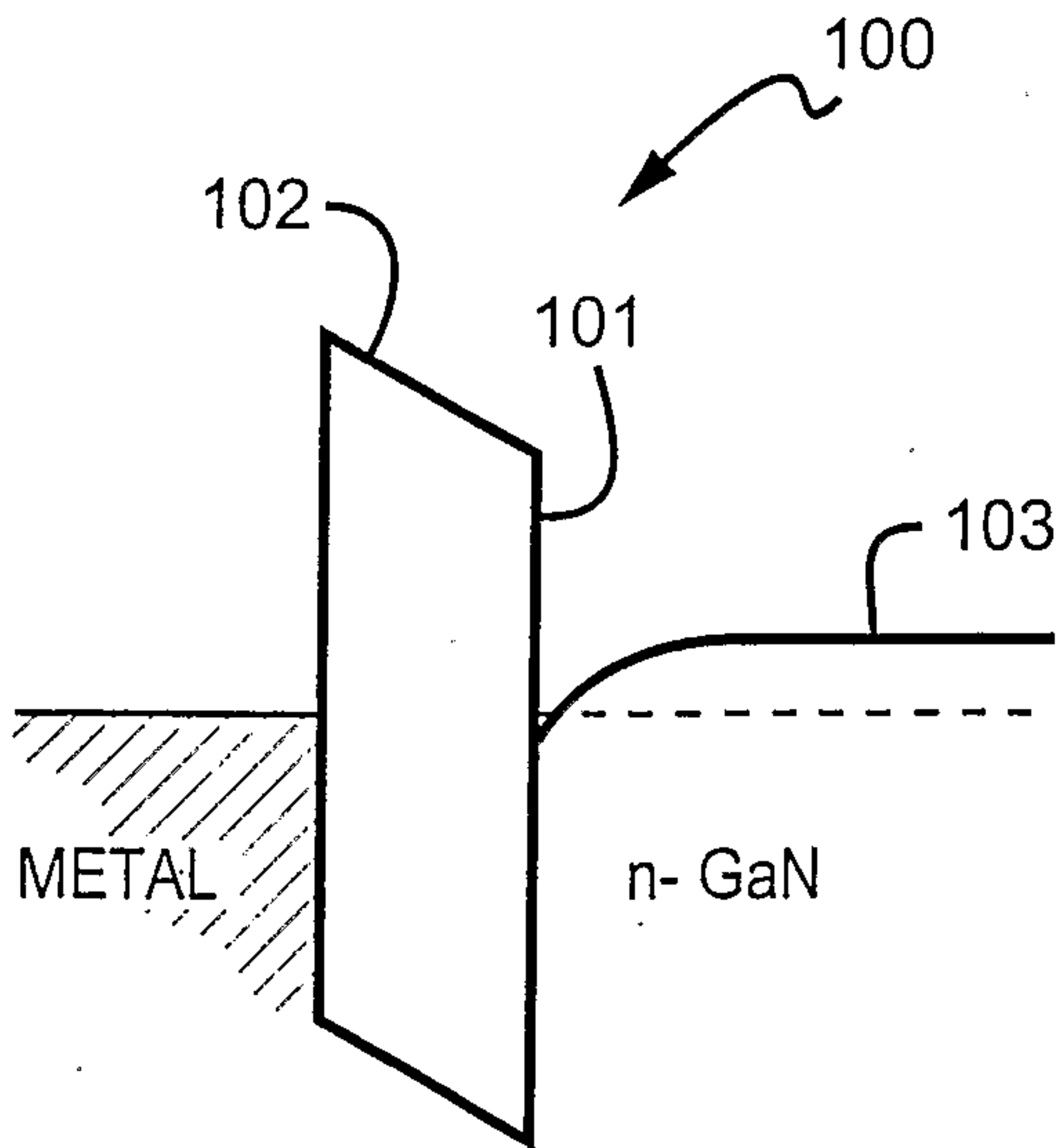


FIG. 10

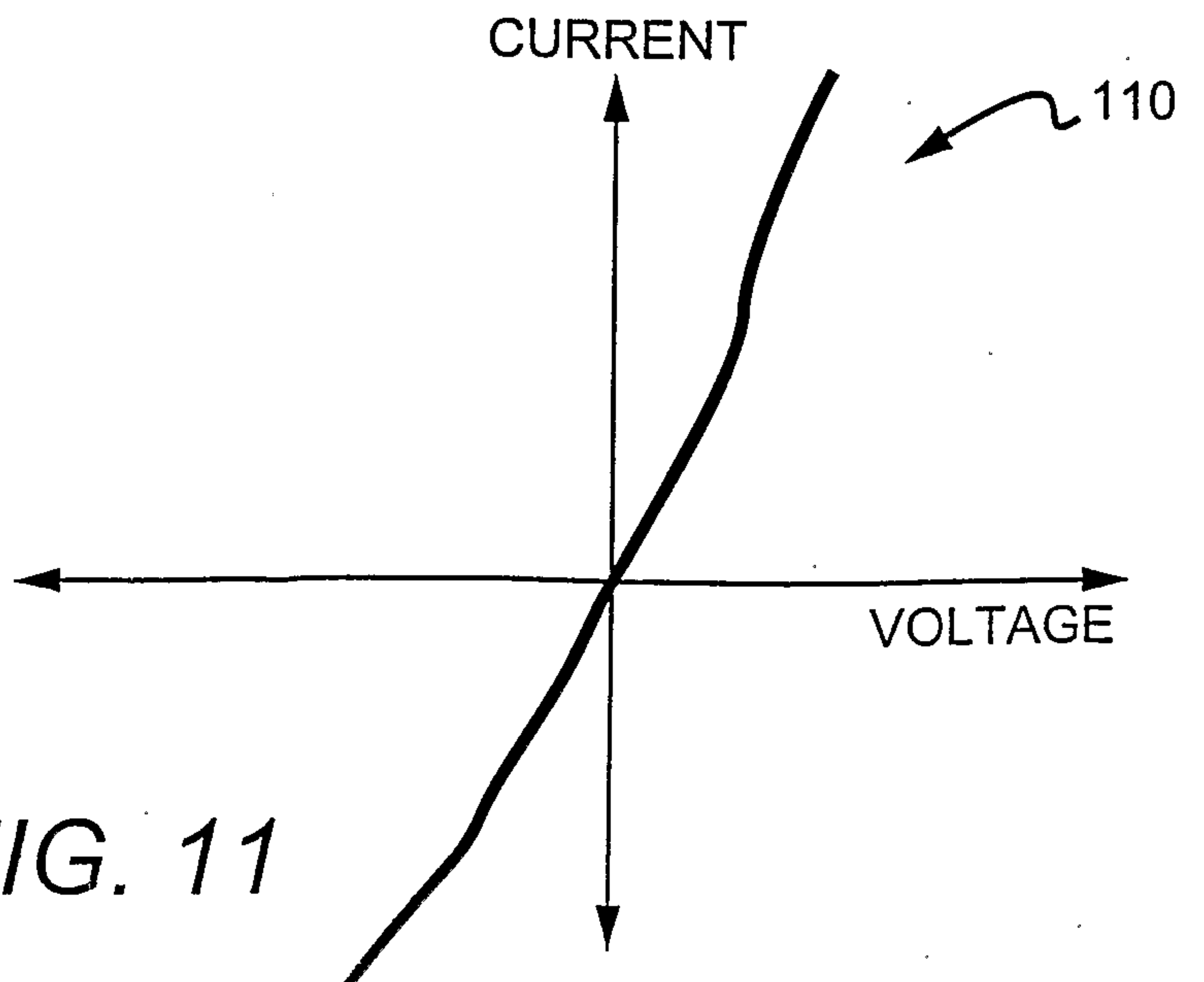
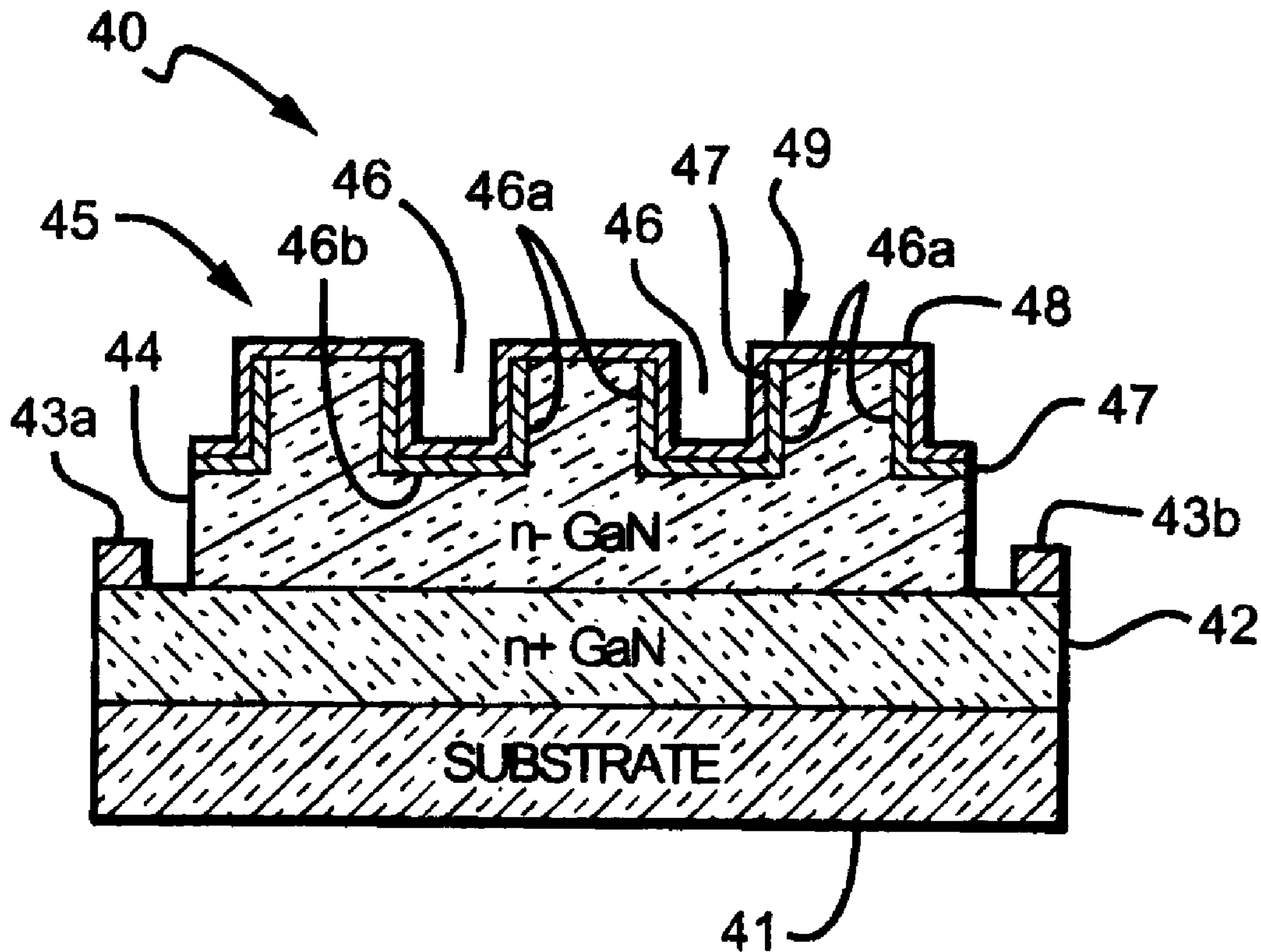


FIG. 11


40
45
46b
46
46a
46
47
49
46a
48
44
43a
47
n- GaN
43b
n+ GaN
42
SUBSTRATE
41