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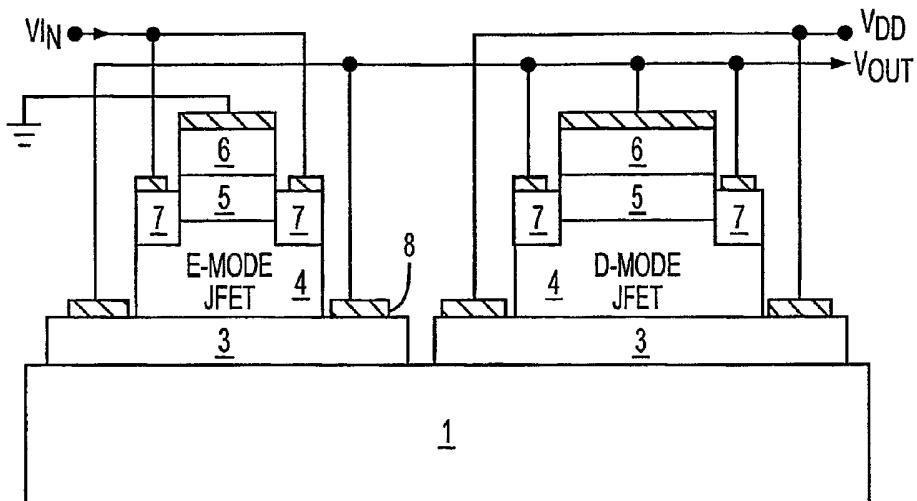
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(57) Abstract: Wide bandgap semiconductor devices including normally-off VJFET integrated power switches are described. The power switches can be implemented monolithically or hybirdly, and may be integrated with a control circuit built in a single-or multi-chip wide bandgap power semiconductor module. The devices can be used in high-power, temperature-tolerant and radiation-resistant electronics components. Methods of making the devices are also described.

NORMALLY-OFF INTEGRATED JFET POWER SWITCHES IN WIDE BANDGAP SEMICONDUCTORS AND METHODS OF MAKING

This application is related to U.S. Patent Application No. 60/585,881, filed July 8, 2004, and U.S. Patent Application No. 10/999,954, filed on December 1, 2004, entitled: "Lateral Trench Field-Effect Transistors in Wide Bandgap Semiconductor Materials, Methods of Making, And Integrated Circuits Incorporating the Transistors". Each of the aforementioned applications is incorporated by reference herein in its entirety.

BACKGROUND

Technical Field

The present invention relates generally to field effect transistors (FETs), and in particular, to such transistors formed in wide bandgap semiconductor materials. Further, this invention relates to monolithic and hybrid integrated circuits comprising low-voltage control circuitry and to power switches built using the above transistors.

Background of the Technology

Wide bandgap semiconductor materials (with $E_G > 2\text{eV}$) such as silicon carbide (SiC) or Group III nitride compound semiconductors (*e.g.*, gallium nitride or GaN) are very attractive for use in high-power, high-temperature, and/or

radiation resistant electronics. Monolithic or hybrid integration of a power transistor and control circuitry in a single or multi-chip wide bandgap power semiconductor module is highly desirable for such applications in order to improve the efficiency and reliability of the system.

SiC smart power technology has been a topic of discussion in recent years, but has experienced limited scientific investigation. Proposed solutions have been met with skepticism relating to the operation of both the power switch and control circuitry.

Because of the fundamental differences in material properties and processing technologies, traditional Si or GaAs integrated circuit (IC) technologies such as Complementary Metal-Oxide-Semiconductor (CMOS) or Direct Coupled FET Logic (DCFL) cannot in most cases be easily transferred to wide bandgap semiconductors. Several attempts at fabricating SiC NMOS and CMOS digital and analog ICs have been reported in the last decade (*e.g.*, [1], [2]). A monolithic CMOS integrated device in SiC and method of fabricating the same is disclosed in U.S. Patent No. 6,344,663, [3]. Moreover, recent development in SiC Lateral DMOS Field-Effect Transistors (LDMOSFETs) (*e.g.*, [4]-[5]) theoretically allow for the monolithic integration of MOSFET-based control circuitry and power switches for use in Smart Power electronics. Various issues, however, limit the use of MOSFET-based SiC integrated circuits in the applications where high-temperature and/or radiation tolerance is required. The first such issue is on-state insulator reliability as a result of a much smaller conduction band offset of SiC to

SiO_2 as compared to that of silicon. This issue becomes even more significant at high temperatures and in extreme radiation environments. Other issues include: low inversion channel mobility due to high interface state density at the SiC/SiO_2 interface and high fixed charge density in the insulator; and significant threshold voltage shift with temperature due to ionization of interface states.

Another transistor candidate for use in SiC Smart Power electronics, a SiC bipolar junction transistor (BJT), also suffers from interface-related issues such as high recombination velocity on the surface between the emitter and the base resulting in low current gain and high control losses.

Another transistor candidate for use in SiC Smart Power electronics is a Metal Semiconductor Field-Effect Transistor (MESFET). Despite the fact the SiC MESFET monolithic microwave integrated circuits (MMICs) received significant development in the last decade (*e.g.*, [6]), there have been few published attempts to build SiC MESFET logic and analog circuits (*e.g.*, [7]).

An alternative to the MOSFET and MESFET approaches is the use of lateral JFET-based integrated circuits implemented in either complementary (n-type and p-type channels as disclosed in U.S. Patent No. 6,503,782 [8]) or enhanced-depletion (n-type channels) forms. SiC JFETs have proven to be radiation tolerant while demonstrating very insignificant threshold voltage shift with temperature. Encouraging results in the development of high-temperature normally-on power vertical junction field-effect transistors (VJFETs) have been published in recent years (*e.g.*, [9]). However, despite their excellent current-

conduction and voltage-blocking capabilities, a major deficiency of these transistors is that they are “normally-on” devices. On the system level, this often requires an additional (negative) supply voltage and short circuit protection.

Several attempts to build normally-off SiC high-voltage VJFET switches have been reported recently. Typically, these devices comprise both lateral and vertical channel regions (*e.g.*, [10]-[12]). These devices, however, exhibit a drastic contradiction between the device blocking capabilities and the specific on-resistance. For example, a VJFET with a 75 μm , $7 \times 10^{14} \text{ cm}^{-3}$ n-type drift region was able to block above 5.5 kV at zero gate-to-source voltage [13]. At the same time, this device demonstrated a specific on-resistance ($R_{\text{sp-on}}$) of more than 200 $\text{m}\Omega \cdot \text{cm}^3$. The intrinsic resistance of its drift layer estimated from its thickness and doping was slightly above 60 $\text{m}\Omega \cdot \text{cm}^3$, with the remainder of the on-resistance was contributed by the channel regions.

In order to reduce the specific on-resistance of SiC power VJFETs, these devices can be driven in bipolar mode by applying high positive gate-to-source voltage. For example, the device discussed above and disclosed in [13] demonstrated an $R_{\text{sp-on}}$ of 66.7 $\text{m}\Omega \cdot \text{cm}^3$ when a gate-to-source bias of 5 V was applied [14]. This approach, however, can lead to significant power losses due to high gate current.

Another approach is to use special circuits and methods for controlling normally-on devices so that they can be operated in normally-off mode. A cascode connection of a low-voltage control JFET with a high-voltage JFET wherein the

drain of the control JFET is connected to the source of the high-voltage device and the gate of high-voltage JFET is connected to the source of the control JFET has been disclosed in U.S. Patent No. 3,767,946 [15]. A compound field-effect transistor monolithically implementing such a cascode connection has also been disclosed in U.S. Patent No. 4,107,725 [16]. Similar types of cascode circuits, where low-voltage normally-off devices control high-voltage normally-on devices are disclosed in U.S. Patent No. 4,663,547 [17]. More recently, a normally-on SiC VJFET controlled by an Si MOSFET in the above configuration has been reported by several groups (e.g., [18]). This integrated power switch has demonstrated excellent voltage-blocking and current-conducting capabilities, as well as high switching speed. However, the use of silicon MOSFETs for the control of power in normally-on SiC VJFETs significantly limits both the temperature range and the radiation tolerance of the cascode. Accordingly, there is still a need for wide bandgap normally-off power switching device in general, and in particular, for such a power switch integrated with control circuitry built in wide bandgap semiconductors.

SUMMARY

According to a first embodiment, a monolithic integrated circuit is provided which comprises:

a substrate having opposed first and second major surfaces; and
first and second junction field-effect transistors on discrete locations on the

first major surface of the substrate, each of the first and second junction field-effect transistors comprising:

 a drain layer of an n-type semiconductor material on and non-coextensive with the first major surface of the substrate such that portions of the substrate surrounding the drain layer are exposed;

 a drift layer of an n-type semiconductor material on and non-coextensive with the drain layer such that portions of the drain layer are exposed, the drift layer having a lower conductivity than the drain layer;

 one or more raised regions on discrete locations on the drift layer, each raised region comprising a channel region of an n-type semiconductor material on the drift layer and a source region of an n-type semiconductor material on the channel region, the semiconductor material of the source region having a higher conductivity than that of the channel region;

 a gate region of a p-type semiconductor material on the drift layer adjacent the one or more raised regions and forming a rectifying junction with n-type material of the drift layer and the channel region(s);

 ohmic contacts on the gate and source regions and on exposed portions of the drain layer;

 a first electrical connection between the source ohmic contact of the first junction field-effect transistor and the gate ohmic contact of the second junction field-effect transistor; and

 a second electrical connection between the drain ohmic contact of the first

junction field-effect transistor and the source ohmic contact of the second junction field-effect transistor.

According to a second embodiment, a monolithic integrated circuit is provided which comprises:

a substrate having opposed first and second major surfaces; and
a buffer layer of a p-type semiconductor material on the first major surface of the substrate;

first and second discrete channel regions each of an n-type semiconductor material in spaced relation on the buffer layer, the second channel region comprising a base portion on the buffer layer and an upper portion, the base portion extending laterally beyond the upper portion so as to form a shoulder;

a source region of an n-type semiconductor material on the buffer layer adjacent to and in contact with the first channel region;

a source/drain region of an n-type semiconductor material on the buffer layer between the first channel region and the second channel region and in contact with both the first channel region and the second channel region, a portion of the source/drain region overlapping the shoulder portion of the second channel region;

a drain region on the shoulder of the second channel region such that the drain region does not directly contact the buffer layer;

a first gate region of a p-type semiconductor material on the first channel region and forming a rectifying junction therewith;

a second gate region of a p-type semiconductor material on an upper surface of the top portion of the second channel region and forming a rectifying junction therewith; and

ohmic contacts on the source region, the first and second gate regions, the source/drain region and the drain region.

According to a third embodiment, an integrated circuit is provided which comprises:

a first vertical channel JFET comprising:

a substrate having opposed first and second surfaces;

a drain layer of an n-type semiconductor material on the first surface of the substrate;

a drift layer of an n-type semiconductor material on and non-coextensive with the drain layer such that portions of the drain layer are exposed, the drift layer having a lower conductivity than the drain layer;

one or more raised regions comprising a channel region of an n-type semiconductor material on the drift layer and a source region of an n-type semiconductor material on the channel region, the material of the source region having a higher conductivity than that of the channel region;

a gate region of a p-type semiconductor material on the drift layer adjacent the one or more raised regions and forming a rectifying junction with the drift layer and the channel region(s);

ohmic contacts the gate and source regions and on exposed portions of the drain layer;

a second vertical channel JFET discrete from the first vertical channel JFET comprising:

a substrate of an n-type semiconductor material having opposed first and second major surfaces;

a drain layer of an n-type semiconductor material on the first major surface of the substrate;

a drift layer of an n-type semiconductor material on the drain layer, the drift layer having a lower conductivity than the drain layer;

one or more raised regions comprising a channel region of an n-type semiconductor material on the drift layer and a source region of an n-type semiconductor material on the channel region, the material of the source region having a higher conductivity than that of the channel region;

a gate region of a p-type semiconductor material on the drift layer adjacent the one or more raised regions and forming a rectifying junction with the drift layer and the channel region(s); and

ohmic contacts on the gate and source regions and on the second major surface of the substrate;

a first electrical connection between the drain ohmic contact of the first vertical channel JFET and the source ohmic contact of the second vertical channel JFET; and

a second electrical connection between the source ohmic contact of the first vertical channel JFET and the gate ohmic contact of the second vertical channel JFET.

According to a fourth embodiment, an integrated circuit is provided which comprises:

a discrete lateral channel JFET comprising:

a substrate having opposed first and second major surfaces;

a buffer layer of a p-type semiconductor material on the first major surface of the substrate;

discrete source and drain regions each of an n-type semiconductor material in spaced relation on the buffer layer;

a channel region of an n-type semiconductor material on the buffer layer between the source and drain regions and in contact with each of the source and drain regions;

a gate region of a p-type semiconductor material on the channel region and forming a rectifying junction therewith;

ohmic contacts on the source, gate, and drain regions;

a discrete vertical channel JFET comprising:

a substrate of an n-type semiconductor material having opposed first and second major surfaces;

a drain layer of an n-type semiconductor material on the first major surface of the substrate;

a drift layer of an n-type semiconductor material on the drain layer, the drift layer having a lower conductivity than the drain layer;

one or more discrete raised regions each comprising a channel region of an n-type semiconductor material on the drift layer and a source region of an n-type semiconductor material on the channel region, the material of the source region having a higher conductivity than that of the channel region;

a gate region of a p-type semiconductor material on the drift layer adjacent the one or more raised regions and forming a rectifying junction with the drift layer and the channel region(s); and

ohmic contacts on the gate and source regions and on the second major surface of the substrate;

a first electrical connection between the drain ohmic contact of the lateral channel JFET and the source ohmic contact of the vertical channel JFET; and

a second electrical connection between the source ohmic contact of the lateral channel JFET and the gate ohmic contact of the vertical channel JFET.

According to a fifth embodiment, a monolithic lateral channel junction field-effect transistor (JFET) is provided which comprises:

a substrate having opposed first and second major surfaces; and

a buffer layer of a p-type semiconductor material on the first major surface of the substrate;

a channel layer of an n-type semiconductor material on the buffer layer;

discrete source and drain regions of an n-type semiconductor material in spaced relation on the channel layer;

a source/drain region of an n-type semiconductor material on the channel layer between the source and drain regions and spaced from each of the source and drain regions;

a first gate region of a p-type semiconductor material formed in the channel layer between the source and source/drain regions and forming a rectifying junction with the channel layer;

a second gate region of a p-type semiconductor material formed in the channel layer between the source/drain and drain regions and forming a rectifying junction with the channel layer;

ohmic contacts on the source region, the first and second gate regions, the source/drain region and the drain region.

According to a sixth embodiment, an integrated circuit is provided which comprises:

a discrete lateral channel JFET comprising:

a substrate having opposed first and second major surfaces; and

a buffer layer of a p-type semiconductor material on the first surface of the substrate;

a channel layer of an n-type semiconductor material on the buffer layer;

discrete source and drain regions of an n-type semiconductor material in spaced relation on the channel layer;

a gate region of a p-type semiconductor material formed in the channel layer between the source and drain regions and forming a rectifying junction with the channel layer;

ohmic contacts on the source region, the gate region, and the drain region;

a discrete vertical channel JFET comprising:

a substrate of an n-type semiconductor material having opposed first and second major surfaces;

a drain layer of an n-type semiconductor material on the first major surface of the substrate;

a drift layer of an n-type semiconductor material on the drain layer, the drift layer having a lower conductivity than the drain layer;

one or more discrete raised regions each comprising a channel region of an n-type semiconductor material on the drift layer and a source region of an n-type semiconductor material on the channel region, the material of the source region having a higher conductivity than that of the channel region;

a gate region of a p-type semiconductor material on the drift layer adjacent the one or more raised regions and forming a rectifying junction with the drift layer and the channel region(s); and

ohmic contacts on the gate and source regions and on the second major surface of the substrate;

a first electrical connection between the source ohmic contact of the lateral channel JFET and the gate ohmic contact of the vertical channel JFET; and

a second electrical connection between the drain ohmic contact of the lateral channel JFET and the source ohmic contact of the vertical channel JFET.

According to a seventh embodiment, a monolithic integrated circuit is provided which comprises a lateral junction field effect transistor and a vertical junction field effect transistor;

the lateral junction field effect transistor comprising:

a buffer layer of a p-type semiconductor material formed in a portion of a first major surface of a drift layer;

a channel layer of an n-type semiconductor material on and non-coextensive with the buffer layer such that a portion of the buffer layer is exposed;

discrete source and drain regions of an n-type semiconductor material in spaced relation on the channel layer;

a gate region of a p-type semiconductor material formed in the channel layer between the source and drain regions and forming a rectifying junction with the channel layer;

ohmic contacts on the source region, the gate region, the drain region and on the exposed portion of the buffer layer;

the vertical junction field effect transistor comprising:

a channel layer of an n-type semiconductor material on the first major surface of the drift layer laterally spaced from the buffer layer;

one or more discrete source regions of an n-type semiconductor material in spaced relation on the channel layer;

a gate region of a p-type semiconductor material formed in the channel layer adjacent the one or more source regions and forming a rectifying junction with the channel layer; and

ohmic contacts on the gate and source regions;

wherein the drift layer is on a drain layer of an n-type semiconductor material which is on a first major surface of a substrate; and wherein an electrical contact is on a second major surface of the substrate opposite the first major surface of the substrate.

According to an eighth embodiment, a monolithic integrated circuit is provided which comprises a lateral junction field effect transistor and a vertical junction field effect transistor;

the lateral junction field effect transistor comprising:

a buffer layer of a p-type semiconductor material formed in a portion of a first major surface of a drift layer;

a channel layer of an n-type semiconductor material on and non-coextensive with the buffer layer such that a portion of the buffer layer is exposed; discrete source and drain regions each of an n-type semiconductor material in spaced relation on the channel layer;

a metal layer on the channel layer between the source and drain regions forming a metal-semiconductor rectifying junction with the channel layer;

ohmic contacts on the source region, the drain region and on the exposed portion of the buffer layer;

the vertical junction field effect transistor comprising:

one or more raised regions on the first major surface of the drift layer laterally spaced from the buffer layer each comprising a channel region of an n-type semiconductor material on the first major surface of the drift layer and spaced from the buffer layer of the lateral junction field effect transistor and a source region of an n-type semiconductor material on the channel region;

a metal layer on the drift layer adjacent to the one or more raised regions forming a metal-semiconductor rectifying junction with the drift layer and the channel region(s); and

an ohmic contact on the source region;

wherein the drift layer is on a layer of n-type semiconductor material which is on a first major surface of a substrate; and wherein an electrical contact is on a second major surface of the substrate opposite the first major surface of the substrate.

BRIEF DESCRIPTION OF THE FIGURES

Figure 1 is a schematic cross-section of a monolithic inverter circuit comprising enhanced and depletion mode LTJFETs.

Figure 2 is a schematic cross-section of a monolithic normally-off JFET comprising enhanced and depletion mode LTJFETs having a built-in PiN diode.

Figures 3A and 3B are a circuit representation (Figure 3A) and an example layout (Figure 3B) of a monolithic normally-off JFET integrated circuit comprising enhanced and depletion mode LTJFETs having a built-in PiN diode.

Figure 4 is a schematic cross-sectional representation of a monolithic normally-off JFET built using enhanced and depletion mode LTJFETs integrated with an SBD or a JBS diode.

Figures 5A and 5B are a circuit representation (Figure 5A) and an example layout (Figure 5B) of a monolithic normally-off JFET integrated circuit comprising enhanced and depletion mode LTJFETs integrated with an SBD or a JBS diode.

Figure 6 is a schematic cross-sectional representation of a hybrid normally-off JFET built using an enhanced mode LTJFET and a depletion mode VJFET having a built-in PiN diode.

Figure 7 is a schematic cross-sectional representation of a hybrid normally-off JFET built using enhanced mode LTJFETs and a depletion mode VJFET integrated with an SBD or a JBS diode.

Figure 8 is a circuit representation of a monolithic LTJFET timer circuit driving a built-on-chip low-voltage high-current enhanced-mode LTJFET connected in cascode with a discrete high-voltage normally-on power VJFET.

Figure 9 is a schematic cross-sectional representation of a monolithic inverter circuit built using enhanced and depletion mode overgrown-gate LJFETs.

Figure 10 is a schematic cross-sectional representation of a hybrid normally-off JFET comprising an enhanced mode overgrown-gate LJFET and a depletion mode VJFET.

Figure 11 is a schematic cross-sectional representation of a hybrid normally-off JFET power-switch comprising a low voltage enhanced mode LJFET and a high voltage discrete normally-on depletion mode VJFET.

Figure 12 is a schematic cross-sectional representation of a monolithic inverter circuit built using enhanced and depletion mode implanted-gate LJFETs.

Figure 13 is a schematic cross-sectional representation of a monolithic normally-off JFET integrated circuit built using enhanced and depletion mode implanted-gate LJFETs.

Figure 14 is a schematic cross-sectional representation of hybrid normally-off JFET integrated circuit built using an enhanced mode implanted-gate LJFET and a depletion mode VJFET.

Figure 15 is a schematic cross-sectional representation of a hybrid normally-off JFET integrated circuit built using an enhanced mode dual-gate

LJFET and a depletion mode VJFET wherein the bottom gate of the LJFET is implanted into the drift region.

Figure 16 is a schematic cross-sectional representation of a hybrid guard-ring terminated normally-off JFET integrated circuit built using an enhanced mode dual-gate LJFET and a depletion mode VJFET wherein the bottom gate of the LJFET and the guard rings are implanted into the drift region.

Figure 17 is a schematic cross-sectional representation of a hybrid guard-ring terminated normally-off JFET built using an enhanced mode dual-gate LJFET and a depletion mode VJFET with a Schottky gate wherein the bottom gate of the LJFET and the guard rings are implanted into the drift region.

Figures 18A-18D are a simulated device structure (Figure 18A), schematic cross sectional representation (Figure 18B) and graphs showing the output DC characteristics (Figures 18C and 18D) of a SiC LTJFET integrated switch.

Figures 19A-19D are a photograph (Figure 19A), circuit representation (Figure 19B) and graphs (Figures 19C and 19D) showing measured characteristics of a hybrid normally-off 900 V power switch.

Figures 20A and 20B are a circuit representation (Figure 20A) and a graph (Figure 20B) showing measured internal voltages of a hybrid normally-off, 900 V power switch.

Figures 21A-21C are schematic representations of distributed drain resistances of an LTJFET (Figure 21A) and a VJFET (Figure 21B) along with a graph (Figure 21C) showing the resistance of the lateral drain layer of an LTJFET

normalized to the resistance of the vertical drain of a VJFET as a function of finger length for different doping levels of the lateral drain layer.

Figures 22A-22H illustrate a method of making a monolithic integrated circuit as set forth in Figures 9 and 10.

Figures 23A-23H illustrate a method of making a monolithic integrated circuit as set forth in Figures 12 and 13.

Figures 24A-24J illustrate a method of making a monolithic integrated circuit as set forth in Figure 15.

Figures 25A-25D illustrate a method of making a monolithic integrated circuit as set forth in Figure 17.

REFERENCE NUMERALS

The reference numerals used in the drawings are defined as set forth below. For the substrate, implanted regions, and epitaxially grown layers, representative thicknesses and doping concentrations are also provided.

#	Material
1	Substrate (e.g., semi-insulating substrate)
1a	N-type substrate (e.g., doping level $>1\times10^{18} \text{ cm}^{-3}$)
2	Epitaxially grown layer (p-type) (e.g., $\geq0.1 \mu\text{m}$ thick, $1\times10^{15} - 1\times10^{17} \text{ cm}^{-3}$)
3	Epitaxially grown layer (n-type) (e.g., $0.2-5 \mu\text{m}$, $>5\times10^{18} \text{ cm}^{-3}$)

3a	Epitaxially grown layer (n-type) (e.g., 0.5-1 μ m, $>5 \times 10^{18}$ cm $^{-3}$)
4	Epitaxially grown layer (n-type) (e.g., 0.5-10 μ m, 5×10^{15} - 5×10^{17} cm $^{-3}$)
4a	Epitaxially grown layer (n-type) (e.g., 5-350 μ m, 2×10^{14} - 2×10^{16} cm $^{-3}$)
5	Epitaxially grown layer (n-type) (e.g., 0.2-1.5 μ m, 5×10^{15} - 5×10^{17} cm $^{-3}$)
5a	Epitaxially grown layer (n-type) (e.g., 0.2-1.5 μ m, 5×10^{15} - 2×10^{17} cm $^{-3}$)
5b	Epitaxially grown layer (n-type) (e.g., 0.3-1.5 μ m, 5×10^{15} - 2×10^{17} cm $^{-3}$)
6	Epitaxially grown layer (n-type) (e.g., 0.2-1.5 μ m, $>5 \times 10^{18}$ cm $^{-3}$)
6a	Implanted region (n-type) (e.g., ≥ 0.1 μ m, $\geq 5 \times 10^{18}$ cm $^{-3}$)
7	Implanted region (p-type) (e.g., ≥ 0.1 μ m, $\geq 5 \times 10^{18}$ cm $^{-3}$)
7a	Epitaxially grown layer (p-type) (e.g., 0.2-1.5 μ m, $>5 \times 10^{18}$ cm $^{-3}$)
8	Ohmic contact
9	Schottky contact

DETAILED DESCRIPTION

The present invention will be described in more detail hereafter with reference to the accompanying drawings and photographs, in which preferred embodiments of the invention are described with silicon carbide (SiC) semiconductor serving as an example.

Silicon carbide crystallizes in numerous (*i.e.*, more than 200) different modifications (polytypes). The most important are: 3C-SiC (cubic unit cell, zincblende); 2H-SiC; 4H-SiC; 6H-SiC (hexagonal unit cell, wurtzite); 15R-SiC (rhombohedral unit cell). The 4H polytype is more attractive for power devices, because of its higher electron mobility. Although the 4H-SiC is preferred, it is to be understood that the present invention is applicable to devices and integrated circuits described herein made of other wide bandgap semiconductor materials such as gallium nitride, and other polytypes of silicon carbide, by way of example.

Figure 1 shows a schematic cross-section of enhanced and depletion mode semiconductor devices referred to a Lateral Trench Junction Field-Effect Transistors (LTJFETs), and a schematic presentation of electrical connections used to form a monolithic inverter circuit. As shown, the devices used to form the inverter are built on a wide bandgap semiconductor substrate (1), which can be either: semi-insulating; p-type; or n-type with a p-type buffer layer. As shown in Figure 1, the devices comprise drain (3), drift (4), channel (5), and source (6) epitaxially grown n-type layers, and p-type implanted gate regions (7). The device structures can be defined using plasma etching and ion implantation. In the

circuit shown in Figure 1, the ohmic contacts to the source, gate, and drain regions can be formed on the same side of the wafer, which allows for the devices to be used in monolithic integrated circuits. A complete description of a device as described above and shown in Figure 1 as well as an exemplary fabrication method for this device can be found in U.S. Patent Application Serial No. 10/999,954, entitled: "Lateral Trench Field-Effect Transistors in Wide Bandgap Semiconductor Materials, methods of Making, and Integrated Circuits Incorporating the Transistors", filed on even date herewith, which application is incorporated by reference herein in its entirety.

Figure 2 is a schematic representation of a monolithic normally-off JFET comprising single-finger enhanced and depletion mode LTJFETs and having a built-in PiN diode. A schematic presentation of electrical connections is also shown in Figure 2. As shown in Figure 2, the devices are connected in cascode configuration in such a way that the drain of the enhanced mode transistor (referred to as an "EJFET") is connected to the source of the depletion mode transistor (referred to as a "DJFET"), and the gate of the DJFET is connected to the source of the control EJFET. The p-n junctions formed in between the gate regions (7) and the drift layer (4) of the DJFET of this device form a so called anti-parallel free-wheeling PiN diode. The size of this diode can be defined by the widths of implanted gate regions.

Although Figure 2 shows single-finger device implementation of a normally-off JFET, in practice multi-finger LTJFETs can be used to form power

switches. Figures 3A and 3B shows a schematic circuit representation (Figure 3A) and an exemplary layout design (Figure 3B) of a monolithic multi-finger normally-off power switch.

In order to reduce switching losses, the PiN diode shown as in Figures 3A and 3B can be replaced with a Schottky Barrier diode (SBD) or a Junction Barrier Schottky (JBS) diode. Methods of forming Schottky gates in a trench structure are disclosed in U.S. Patent Application No. 60/585,881, filed July 8, 2004, which application is incorporated by reference herein in its entirety. Figure 4 provides a schematic cross-section of a monolithic normally-off JFET power switch with an integrated free-wheeling SBD or JBS diode, and Figures 5A and 5B provide a schematic circuit representation (Figure 5A) and exemplary layout design (Figure 5B) of such a switch monolithically formed using multi-finger LTJFETs.

Figures 6 and 7 are schematic cross-sectional representations of single-finger normally-off JFET power switches where enhancement-mode low-voltage LTJFETs control high-voltage discrete normally-on depletion-mode VJFETs.

Figure 6 shows a hybrid JFET power switch with a built-in anti-parallel PiN diode, and Figure 7 shows a JFET power switch comprising an anti-parallel SBD or JBS diode monolithically integrated with a high-voltage VJFET.

An exemplary implementation of the technology described above is shown in Figure 8. As shown in Figure 8, a monolithic LTJFET timer circuit drives a built-on-chip low-voltage high-current enhanced-mode LTJFET connected in cascode with a discrete high-voltage normally-on power VJFET.

Although vertical channel multi-finger LTJFETs are preferable in high-power application because of their low specific on-resistance and absence of trapping effects common in wide bandgap semiconductors, alternative JFET structures (*e.g.*, those with a lateral channel) can also be employed to form normally-off power JFET switches. Figures 9-17 illustrate various exemplary embodiments of integrated JFET switches built using enhanced and depletion mode Lateral Junction Field-Effect Transistors (LJFETs).

Figure 9 is a schematic cross-sectional representation with electrical connections of a lateral channel JFET integrated circuit comprising enhanced and depletion mode LJFETs having epitaxially overgrown gates. As shown in Figure 9, the integrated circuit forms a monolithic inverter circuit. The LJFETs used to form the inverter are built on the wide bandgap semiconductor substrate (1), which can be either: semi-insulating; p-type; or n-type with a p-type buffer layer. As shown in Figure 9, the integrated circuit comprises buffer (2) and channel (5a) epitaxially grown n-type layers, as well as implanted source and drain (6a) regions and epitaxially grown p-type gate regions (7a). The device structures can be defined using plasma etch and ion implantation. The ohmic contacts (8) to the source, gate, and drain regions can be formed on the same side of the wafer allowing for the use of the device in monolithic integrated circuits.

Figure 10 is a schematic representation of a pitch of a monolithic normally-off JFET power switch built using enhanced and depletion mode LJFETs with overgrown gate regions. As can be seen from the schematic presentation of

electrical connections, the devices are connected in cascode configuration in such a way that the drain of the low-voltage enhanced mode LJFET (referred to as an “ELJFET”) is connected to the source of the higher-voltage depletion mode LJFET (referred to as a “DLJFET”), and the gate of the DLJFET is connected to the source of the control ELJFET.

Figure 11 shows a schematic cross-section of a hybrid normally-off JFET power switch wherein a low-voltage ELJFET controls a high-voltage discrete normally-on depletion-mode VJFET.

An alternative LJFET structure where source and drain regions are formed in an epitaxially grown n-type layer and gate regions are defined by ion implantation can also be used. Devices of this type are shown in Figures 12-17.

Figure 12 shows is a schematic cross-sectional representation with electrical connections of a monolithic inverter circuit comprising enhanced and depletion mode implanted-gate LJFETs. As shown, the devices used to form the inverter are built on a wide bandgap semiconductor substrate (1), which can be either: semi-insulating; p-type; or n-type with a p-type buffer layer. As also shown, the device comprises buffer (2), channel (5b), source and drain (6) epitaxially grown n-type layers, as well as implanted gate (7) regions.

Figure 13 is a schematic cross-sectional representation of a pitch of a monolithic normally-off JFET power switch built using enhanced and depletion mode implanted-gate LJFETs. As shown in Figure 13, the drain of the D-mode

LJFET is laterally spaced from the gate on the channel layer (5b) to form a lateral drift region in the device.

Figure 14 is a schematic cross-sectional representation of a normally-off JFET power switch where an enhancement-mode low-voltage implanted-gate LJFET controls a high-voltage discrete normally-on depletion-mode VJFET.

Figure 15 is a schematic cross-sectional representation of a monolithic normally-off JFET power switch wherein an enhancement-mode low-voltage dual-gate LJFET controls a high-voltage discrete normally-on depletion-mode VJFET. As shown in Figure 15, the bottom gate of the LJFET is implanted into drift region (4) before the channel region is grown thereon.

Figure 16 is a schematic cross-sectional representation of a device as shown in Figure 3D wherein the bottom gate of the LJFET is implanted into drift region 4 together with guard rings. The guard rings can be used to increase the voltage blocking capability of the switch.

Although FET devices having implanted p-type gates are described above, Schottky gates can also be employed for the fabrication of a normally-off FET power switch. Figure 17 is a schematic cross-sectional representation of a device as shown in Figure 16 wherein the implanted p-type top gate of the LJFET and the implanted gate of the discrete normally-on depletion-mode VJFET are replaced with Schottky gates. As shown, the Schottky gate of the discrete normally-on FET also serves as an integrated anti-parallel free-wheeling diode.

Figures 18A-18D shows a simulated device structure (Figure 18A), schematic cross-sectional representation (Figure 18B) and graphs showing the output DC characteristics (Figures 18C and 18D) of a SiC LTJFET integrated switch, where both the EJFET and the DJFET have channel peripheries of 1 cm.

In order to demonstrate feasibility of the above described cascode power switch, a hybrid embodiment of the switch was constructed using discrete non-terminated enhanced and depletion mode vertical JFETs. Figures 19A-19D are a photograph (Figure 19A), a schematic representation (Figure 19B) and graphs showing measured characteristics (Figures 19C and 19D) of a hybrid normally-off, 900 V power switch. As can be seen from Figures 19C and 19D, despite relatively high leakage current ($I_D=330 \mu A$ @ $V_{DS}=900 V$ and $V_{GS}=0 V$) induced by the depletion mode device, the voltage-controlled SiC power switch was controlled by as little as 2.75 V.

The basic function of the switch can be described as follows. At the HIGH control level (*e.g.*, $V_{GS}=2.75 V$), the enhanced mode transistor (EJFET) is turned on. Between the gate and source of the depletion mode transistor (DJFET) only a small voltage drop occurs, therefore, DJFET is on too. If EJFET is turned off with the LOW control level ($V_{GS}=0.25 V$) its drain-to-source voltage increases to 40-50V as shown in Figure 20B. This voltage pinches-off the DJFET.

The specific on-resistance of the integrated switch can be minimized as follows. First, the ratios of pinch-off voltages and channel peripheries of both transistors (*e.g.*, EJFET and DJFET) can be adjusted so that they will have

approximately equal on-resistances and neither one will therefore limit the overall current. Second, the device can be constructed such that the gate-to-source breakdown voltage of DJFET is equal or higher than the drain-to-source breakdown voltage of EJFET.

In addition, the finger length of high-current multi-finger LTJFETs can be reduced to keep the resistances of the alteral drain region compatible to the resistance of the vertical n^+ substrate. Figures 21A and 21 B are schematic representations of distributed drain resistances of LTJFET (Figure 21A) and VJFET (Figure 21B), and graph (Figure 21C) showing resistance of the lateral drain layer of LTJFET normalized to the resistance of the vertical drain of VJFET as a function of finger length for different dopings of the lateral drain layer. As can be seen from Figure 21C, for a heavily doped 1- μm thick lateral drain layer (3), the finger length of the LTJFET will preferably not exceed 100 μm in length. The finger length, however, can be increased by increasing the thickness and/or the doping levels of the drain layer (3).

Figures 22A-22H illustrate a method of making a device as set forth in Figure 9. Figure 22A shows a multi-layer structure comprising a substrate (1), an epitaxially grown p-type layer (2), and an epitaxially grown n-type layer (5a). An etch mask (10) is positioned on the exposed surface of epitaxially grown n-type layer (5a) as shown in Figure 22B. Epitaxially grown n-type layer (5a) is then selectively etched (12) as shown in Figure 22B. Etch mask (10) is then removed and ion implantation mask (14) is then placed on the etched surface of epitaxially

grown n-type layer (5a) as shown in Figure 22D. Ion implantation of n-type dopants through mask (14) results in the formation of highly n-doped regions (6a) in epitaxially grown n-type layer (5a) as shown in Figure 22E. Mask (14) is then removed and a layer of p-type semiconductor material (7a) is grown on the etched and implanted surface of epitaxially grown n-type layer (5a) as shown in Figure 22F. Etch mask (16) is then positioned on the exposed surface of layer (7a) as shown in Figure 22G. Etching through mask (16) results in selective removal of layer (7a) and formation of raised p-type features as also shown in Figure 22G. Finally, mask (16) is removed and ohmic contacts are formed on exposed surfaces of the raised p-type features and the implanted regions (6a).

The method as outlined above can also be used, by selecting appropriate masks, to form a structure as shown in Figure 10.

Figures 23A-23H illustrate a method of making a structure as shown in Figure 12. Figure 23A shows a substrate (1), an epitaxially grown p-type layer (2) on the substrate (1), and an epitaxially grown n-type layer (5b) on layer (2). As shown in Figure 23B, an etch mask (18) is positioned on the exposed surface of layer (5b). Etching (20) results in selective removal of material from layer (5b) as shown in Figure 23C. After removal of mask (18), an n-type epitaxial layer (6) is grown on the etched surface of layer (5b) as shown in Figure 23D. Etch mask (22) is positioned on the exposed surface of layer (6) as shown in Figure 23E and etching (24) results in selective removal of material from layer (6) and exposure of underlying layer (5b) as shown in Figure 23F. Mask (22) is then used to

selectively implant p-type donors in exposed surface of layer (5b) to form implanted gate regions (7) as shown in Figure 23G. Ohmic contacts (8) are then formed on the implanted p-type gate regions (7) to form the gate contacts and on the raised n-type regions (6) to form the source and drain contacts for the device as shown in

Figure 23H.

The method as outlined above can also be used, by selecting appropriate masks, to form a structure as shown in Figure 13.

Figures 24A-24J illustrate a method of making a structure as shown in Figure 15. Figure 24A shows an n-type substrate (1a), an epitaxially grown n-type layer (3a) on substrate (1a), and an epitaxially grown n-type layer (4a) on layer (3a). An ion implantation mask (26) is also shown on the exposed upper surface of layer (4a). As shown in Figure 24B, layer (4a) is selectively implanted with p-type donor atoms through mask (26) to form gate region (7). After removal of mask (26), an n-type epitaxial layer (5) and an n-type epitaxial layer (6) are successively grown on the implanted surface of layer (4a) as shown in Figures 24C and 24D.

Etch mask (30) is then positioned on the exposed surface of layer (6) as shown in Figure 24D followed by etching (31) through layer (6) and partially through underlying layer (5) (Figure 24E). Exposed portions of layer (5) are then implanted with p-type donor atoms through mask (30) to form additional gate regions (7) as shown in Figure 24F. Etch mask (34) is then positioned on the surface of the etched and implanted structure and etching (36) results in selective

removal of portions of layer (5) including portions of the p-type implanted gate regions

(Figure 24H). Exposed portions of layer (4a) are then etched (40) thorough mask (38) as shown in Figure 24I. Ohmic contacts (8) are then formed on the etched and implanted structure to form the device as shown in Figure 24J.

The method as outlined above can also be used to form a structure as shown in Figure 16.

Figures 25A-25D illustrate a method of making a structure as shown in Figure 17. As shown in Figure 25A, a structure a shown in Figure 24E is etched (44) through mask (42) to expose portions of underlying layer (4a) (Figure 25B). Schottky contacts (9) are then formed on the etched/implanted structure as shown in Figure 25C. The formation of ohmic contacts (8) results in the device as shown in Figure 25D.

Although exemplary embodiments are discussed above, other alternative embodiments are also possible. For example, GaN n-type epitaxial layers can be grown on silicon carbide, sapphire, or silicon substrates to form a starting material stack for the fabrication of the proposed device structure. Alternatively, a substrate material comprising a conducting SiC substrate with a semi-insulating epitaxially grown buffer layer can be used as disclosed in U.S. Patent Application Serial No.10/033,785, filed January 3, 2002 (published as U.S. Patent Publication No. 2002-0149021).

The SiC layers can be formed by doping the layers with donor or acceptor materials using known techniques. Exemplary donor materials include nitrogen and phosphorus. Nitrogen is a preferred donor material. Exemplary acceptor materials for doping SiC include boron and aluminum. Aluminum is preferred acceptor material. The above materials are merely exemplary, however, and any acceptor and donor materials which can be doped into silicon carbide can be used. The doping levels and thicknesses of the various layers of the LTJFETs, LJFETs and VJFETs described herein can be varied to produce a device having desired characteristics for a particular application. Similarly, the dimensions of the various features of the device can also be varied to produce a device having desired characteristics for a particular application.

The SiC layers can be formed by epitaxial growth on a suitable substrate. The layers can be doped during epitaxial growth.

While the foregoing specifications teach the principles of the present invention, with examples provided for the purpose of illustration, it will be appreciated by one skilled in the art from reading this disclosure that various changes in form and detail can be made without departing from the true scope of the invention.

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WHAT IS CLAIMED IS:

1. A monolithic integrated circuit comprising:
 - a substrate having opposed first and second major surfaces; and
 - first and second junction field-effect transistors on discrete locations on the first major surface of the substrate, each of the first and second junction field-effect transistors comprising:
 - a drain layer of an n-type semiconductor material on and non-coextensive with the first major surface of the substrate such that portions of the substrate surrounding the drain layer are exposed;
 - a drift layer of an n-type semiconductor material on and non-coextensive with the drain layer such that portions of the drain layer are exposed, the drift layer having a lower conductivity than the drain layer;
 - one or more raised regions on discrete locations on the drift layer, each raised region comprising a channel region of an n-type semiconductor material on the drift layer and a source region of an n-type semiconductor material on the channel region, the semiconductor material of the source region having a higher conductivity than that of the channel region;
 - a gate region of a p-type semiconductor material on the drift layer adjacent the one or more raised regions and forming a rectifying junction with n-type material of the drift layer and the channel region(s);
 - ohmic contacts on the gate and source regions and on exposed portions of the drain layer;

a first electrical connection between the source ohmic contact of the first junction field-effect transistor and the gate ohmic contact of the second junction field-effect transistor; and

a second electrical connection between the drain ohmic contact of the first junction field-effect transistor and the source ohmic contact of the second junction field-effect transistor.

2. The integrated circuit of Claim 1, wherein the semiconductor material of each of the drain layer, drift layer, gate region, channel region and source region has an E_G of at least 2 eV.

3. The integrated circuit of Claim 2, wherein the semiconductor material of each of the drain layer, drift layer, gate region, channel region and source region is SiC or a Group III nitride compound semiconductor material.

4. The integrated circuit of Claim 1, wherein: the drain layer has a thickness of 0.2 to 5 μm ; the drift layer has a thickness of 0.5 to 10 μm ; the channel region has a thickness of 0.2 to 1.5 μm ; the source region has a thickness of 0.2 to 1.5 μm ; and the gate region has a thickness of 0.1 μm or more.

5. The integrated circuit of Claim 1, wherein: the drain layer has a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$; the drift layer has a dopant concentration of 5×10^{15} to $5 \times 10^{17} \text{ cm}^{-3}$; the channel region has a dopant concentration of 5×10^{15} to $5 \times 10^{17} \text{ cm}^{-3}$; the source region has a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$; and the gate region has a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$.

6. The integrated circuit of Claim 1, wherein the substrate is a semi-insulating substrate.
7. The integrated circuit of Claim 1, wherein the second field effect transistor further comprises a Schottky junction comprising a Schottky channel region of an n-type semiconductor material on the drift layer adjacent to and in electrical communication with the gate region and a metal layer on the Schottky channel region forming a metal-semiconductor rectifying junction with the Schottky channel region, the integrated circuit further comprising a third electrical connection between the Schottky metal contact and the first electrical connection.
8. The integrated circuit of Claim 1, wherein the Schottky channel region has a thickness of 0.2 to 1.5 μm and a dopant concentration of 5×10^{15} to 5×10^{17} cm^{-3} .
9. A monolithic integrated circuit comprising:
 - a substrate having opposed first and second major surfaces; and
 - a buffer layer of a p-type semiconductor material on the first major surface of the substrate;
 - first and second discrete channel regions each of an n-type semiconductor material in spaced relation on the buffer layer, the second channel region comprising a base portion on the buffer layer and an upper portion, the base portion extending laterally beyond the upper portion so as to form a shoulder;
 - a source region of an n-type semiconductor material on the buffer layer adjacent to and in electrical communication with the first channel region;

a source/drain region of an n-type semiconductor material on the buffer layer between the first channel region and the second channel region and in electrical communication with both the first channel region and the second channel region, a portion of the source/drain region overlapping the shoulder portion of the second channel region;

a drain region on the shoulder of the second channel region such that the drain region does not directly contact the buffer layer;

a first gate region of a p-type semiconductor material on the first channel region and forming a rectifying junction therewith;

a second gate region of a p-type semiconductor material on an upper surface of the top portion of the second channel region and forming a rectifying junction therewith; and

ohmic contacts on the source region, the first and second gate regions, the source/drain region and the drain region.

10. The integrated circuit of Claim 9, wherein: the buffer layer has a thickness of at least 0.1 μm ; the first and second channel regions each have a thickness of 0.2 to 1.5 μm ; the source, source/drain and drain regions each have a thickness of at least 0.1 μm ; and the first and second gate regions each have a thickness of 0.2 to 1.5 μm or more.

11. The integrated circuit of Claim 9, wherein: the buffer layer has a dopant concentration of 1×10^{15} to 1×10^{17} cm^{-3} ; the first and second channel regions each have a dopant concentration of 5×10^{15} to 2×10^{17} cm^{-3} ; the source, source/drain

and drain regions each have a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$; and the first and second gate regions each have a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$.

12. The integrated circuit of Claim 9, wherein the substrate is a semi-insulating substrate.

13. The integrated circuit of Claim 9, wherein the second channel region has a thickness greater than the first channel region.

14. The integrated circuit of Claim 9, further comprising an electrical connection between the second gate contact and the source/drain contact.

15. The integrated circuit of Claim 9, further comprising an electrical connection between the second gate region and the source region.

16. The integrated circuit of Claim 9, wherein the drain region is laterally spaced from the second gate region forming a lateral drift region in the top portion of the second channel region.

17. The integrated circuit of Claim 9, wherein the semiconductor material of each of the buffer layer, drain region, source/drain region, drift layer, first and second gate regions, first and second channel regions and source region has an E_G of at least 2 eV.

18. The integrated circuit of Claim 17, wherein the semiconductor material of each of the buffer layer, drain region, source/drain region, drift layer, first and second gate regions, first and second channel regions and source region is SiC or a Group III nitride compound semiconductor material.

19. An integrated circuit comprising:

a first vertical channel JFET comprising:

a substrate having opposed first and second surfaces;

a drain layer of an n-type semiconductor material on the first surface of the substrate;

a drift layer of an n-type semiconductor material on and non-coextensive with the drain layer such that portions of the drain layer are exposed, the drift layer having a lower conductivity than the drain layer;

one or more raised regions comprising a channel region of an n-type semiconductor material on the drift layer and a source region of an n-type semiconductor material on the channel region, the material of the source region having a higher conductivity than that of the channel region;

a gate region of a p-type semiconductor material on the drift layer adjacent the one or more raised regions and forming a rectifying junction with the drift layer and the channel region(s);

ohmic contacts the gate and source regions and on exposed portions of the drain layer;

a second vertical channel JFET discrete from the first vertical channel JFET comprising:

a substrate of an n-type semiconductor material having opposed first and second major surfaces;

a drain layer of an n-type semiconductor material on the first major surface of the substrate;

a drift layer of an n-type semiconductor material on the drain layer, the drift layer having a lower conductivity than the drain layer;

one or more raised regions comprising a channel region of an n-type semiconductor material on the drift layer and a source region of an n-type semiconductor material on the channel region, the material of the source region having a higher conductivity than that of the channel region;

a gate region of a p-type semiconductor material on the drift layer adjacent the one or more raised regions and forming a rectifying junction with the drift layer and the channel region(s); and

ohmic contacts on the gate and source regions and on the second major surface of the substrate;

a first electrical connection between the drain ohmic contact of the first vertical channel JFET and the source ohmic contact of the second vertical channel JFET; and

a second electrical connection between the source ohmic contact of the first vertical channel JFET and the gate ohmic contact of the second vertical channel JFET.

20. The integrated circuit of Claim 19, wherein for the first vertical channel JFET: the drain layer has a thickness of 0.2 to 5 μm ; the drift layer has a thickness of 0.5 to 10 μm ; the channel region has a thickness of 0.2 to 1.5 μm ; the source region has a thickness of 0.2 to 1.5 μm ; and the gate region has a thickness of 0.1 μm or more.

21. The integrated circuit of Claim 19, wherein for the first vertical channel JFET: the drain layer has a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$; the drift layer has a dopant concentration of 5×10^{15} to $5 \times 10^{17} \text{ cm}^{-3}$; the channel region has a dopant concentration of 5×10^{15} to $5 \times 10^{17} \text{ cm}^{-3}$; the source region has a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$; and the gate region has a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$.

22. The integrated circuit of Claim 19, wherein for the first vertical channel JFET the substrate is a semi-insulating substrate.

23. The integrated circuit of Claim 19, wherein for the second vertical channel JFET: the drain layer has a thickness of 0.5 to 1 μm ; the drift layer has a thickness of 5 to 350 μm ; the channel region has a thickness of 0.2 to 1.5 μm ; the source region has a thickness of 0.2 to 1.5 μm ; and the gate region has a thickness of 0.1 μm or more.

24. The integrated circuit of Claim 19, wherein for the second vertical channel JFET: the drain layer has a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$; the drift layer has a dopant concentration of 2×10^{14} to $2 \times 10^{16} \text{ cm}^{-3}$; the channel region has a dopant concentration of 5×10^{15} to $5 \times 10^{17} \text{ cm}^{-3}$; the source region has a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$; and the gate region has a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$.

25. The integrated circuit of Claim 19, wherein for the second vertical channel JFET the substrate is an n-type substrate having a dopant concentration of $> 1 \times 10^{18} \text{ cm}^{-3}$.

26. The integrated circuit of Claim 19, wherein the second vertical channel JFET further comprises a Schottky junction comprising a Schottky channel region of an n-type semiconductor material on the drift layer adjacent to and in electrical communication with the gate region and a metal layer on the Schottky channel region forming a metal-semiconductor rectifying junction with the Schottky channel region, the integrated circuit further comprising a third electrical connection between the Schottky metal contact and the first electrical connection.

27. The integrated circuit of Claim 19, wherein the Schottky channel region has a thickness of 0.2 to 1.5 μm and a dopant concentration of 5×10^{15} to 5×10^{17} cm^{-3} .

28. The integrated circuit of Claim 19, wherein, for each of the first and second vertical channel JFETs, the semiconductor material of each of the drain layer, drift layer, channel region, source region and gate region has an E_G of at least 2 eV.

29. The integrated circuit of Claim 28, wherein, for each of the first and second vertical channel JFETs, the semiconductor material of each of the drain layer, drift layer, channel region, source region and gate region is SiC or a Group III nitride compound semiconductor material.

30. An integrated circuit comprising:

a discrete lateral channel JFET comprising:

a substrate having opposed first and second major surfaces;

a buffer layer of a p-type semiconductor material on the first major surface of the substrate;

discrete source and drain regions each of an n-type semiconductor material in spaced relation on the buffer layer;

a channel region of an n-type semiconductor material on the buffer layer between the source and drain regions and in electrical communication with each of the source and drain regions;

a gate region of a p-type semiconductor material on the channel region and forming a rectifying junction therewith;

ohmic contacts on the source, gate, and drain regions;

a discrete vertical channel JFET comprising:

a substrate of an n-type semiconductor material having opposed first and second major surfaces;

a drain layer of an n-type semiconductor material on the first major surface of the substrate;

a drift layer of an n-type semiconductor material on the drain layer, the drift layer having a lower conductivity than the drain layer;

one or more discrete raised regions each comprising a channel region of an n-type semiconductor material on the drift layer and a source region of an n-type semiconductor material on the channel region, the material of the source region having a higher conductivity than that of the channel region;

a gate region of a p-type semiconductor material on the drift layer adjacent the one or more raised regions and forming a rectifying junction with the drift layer and the channel region(s); and

ohmic contacts on the gate and source regions and on the second major surface of the substrate;

a first electrical connection between the drain ohmic contact of the lateral channel JFET and the source ohmic contact of the vertical channel JFET; and

a second electrical connection between the source ohmic contact of the lateral channel JFET and the gate ohmic contact of the vertical channel JFET.

31. The integrated circuit of Claim 30, wherein for the lateral channel JFET: the buffer layer has a thickness of at least 0.1 μm ; the channel region has a thickness of 0.2 to 1.5 μm ; the source and drain regions each have a thickness of at least 0.1 μm ; and the gate region has a thickness of 0.2 to 1.5 μm or more.

32. The integrated circuit of Claim 30, wherein for the lateral channel JFET: the buffer layer has a dopant concentration of 1×10^{15} to $1 \times 10^{17} \text{ cm}^{-3}$; the channel region has a dopant concentration of 5×10^{15} to $2 \times 10^{17} \text{ cm}^{-3}$; the source and drain regions each have a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$; and the gate region has a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$.

33. The integrated circuit of Claim 30, wherein for the lateral channel JFET the substrate is a semi-insulating substrate.

34. The integrated circuit of Claim 30, wherein for the vertical channel JFET: the drain layer has a thickness of 0.5 to 1 μm ; the drift layer has a thickness

of 5 to 350 μm ; the channel region has a thickness of 0.2 to 1.5 μm ; the source region has a thickness of 0.2 to 1.5 μm ; and the gate region has a thickness of 0.1 μm or more.

35. The integrated circuit of Claim 30, wherein for the vertical channel JFET: the drain layer has a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$; the drift layer has a dopant concentration of 2×10^{14} to $2 \times 10^{16} \text{ cm}^{-3}$; the channel region has a dopant concentration of 5×10^{15} to $5 \times 10^{17} \text{ cm}^{-3}$; the source region has a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$; and the gate region has a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$.

36. The integrated circuit of Claim 30, wherein for the vertical channel JFET the substrate is an n-type substrate having a dopant concentration of $> 1 \times 10^{18} \text{ cm}^{-3}$.

37. The integrated circuit of Claim 30, wherein for the lateral channel JFET the semiconductor material of each of the buffer layer, drain region, source region, gate region and channel region has an E_G of at least 2 eV.

38. The integrated circuit of Claim 37, wherein for the lateral channel JFET the semiconductor material of each of the buffer layer, drain region, source region, gate region and channel region is SiC or a Group III nitride compound semiconductor material.

39. The integrated circuit of Claim 30, wherein, for the vertical channel JFET, the semiconductor material of each of the drain layer, drift layer, channel region, source region and gate region has an E_G of at least 2 eV.

40. The integrated circuit of Claim 39, wherein for the vertical channel JFET, the semiconductor material of each of the drain layer, drift layer, channel region, source region and gate region is SiC or a Group III nitride compound semiconductor material.

41. A monolithic lateral channel junction field-effect transistor (JFET) comprising:

a substrate having opposed first and second major surfaces; and

a buffer layer of a p-type semiconductor material on the first major surface of the substrate;

a channel layer of an n-type semiconductor material on the buffer layer;

discrete source and drain regions of an n-type semiconductor material in spaced relation on the channel layer;

a source/drain region of an n-type semiconductor material on the channel layer between the source and drain regions and spaced from each of the source and drain regions;

a first gate region of a p-type semiconductor material formed in the channel layer between the source and source/drain regions forming a rectifying junction with the channel layer;

a second gate region of a p-type semiconductor material formed in the channel layer between the source/drain and drain regions forming a rectifying junction with the channel layer; and

ohmic contacts on the source region, the first and second gate regions, the source/drain region and the drain region.

42. The transistor of Claim 41, wherein: the buffer layer has a thickness of at least 0.1 μm ; the channel layer has a thickness of 0.3 to 1.5 μm ; the source, source/drain and drain regions each have a thickness of 0.2 to 1.5 μm ; and the first and second gate regions each have a thickness of 0.1 μm or more.

43. The transistor of Claim 41, wherein: the buffer layer has a dopant concentration of 1×10^{15} to $1 \times 10^{17} \text{ cm}^{-3}$; the channel layer has a dopant concentration of 5×10^{15} to $5 \times 10^{17} \text{ cm}^{-3}$; the source, source/drain and drain regions each have a concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$; and the first and second gate regions each have a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$.

44. The transistor of Claim 41, wherein the substrate is a semi-insulating substrate.

45. The transistor of Claim 41, further comprising an electrical connection between the source/drain ohmic contact and the second gate region.

46. The transistor of Claim 41, further comprising an electrical connection between the source ohmic contact and the second gate region.

47. The transistor of Claim 41, wherein the drain region is laterally spaced from the second gate region forming a lateral drift region in the channel layer between the second gate region and the drain region.

48. The transistor of Claim 41, wherein for the lateral channel JFET the semiconductor material of each of the buffer layer, drain region, source/drain

region, source region, first and second gate regions and channel layer has an E_G of at least 2 eV.

49. The transistor of Claim 48, wherein for the lateral channel JFET the semiconductor material of each of the buffer layer, drain region, source/drain region, source region, first and second gate regions and channel layer is SiC or a Group III nitride compound semiconductor material.

50. An integrated circuit comprising:

a discrete lateral channel JFET comprising:

a substrate having opposed first and second major surfaces; and

a buffer layer of a p-type semiconductor material on the first surface of the substrate;

a channel layer of an n-type semiconductor material on the buffer layer;

discrete source and drain regions of an n-type semiconductor material in spaced relation on the channel layer;

a gate region of a p-type semiconductor material formed in the channel layer between the source and drain regions forming a rectifying junction with the channel layer;

ohmic contacts on the source region, the gate region, and the drain region;

a discrete vertical channel JFET comprising:

a substrate of an n-type semiconductor material having opposed first and second major surfaces;

a drain layer of an n-type semiconductor material on the first major surface of the substrate;

a drift layer of an n-type semiconductor material on the drain layer, the drift layer having a lower conductivity than the drain layer;

one or more discrete raised regions each comprising a channel region of an n-type semiconductor material on the drift layer and a source region of an n-type semiconductor material on the channel region, the material of the source region having a higher conductivity than that of the channel region;

a gate region of a p-type semiconductor material on the drift layer adjacent the one or more raised regions and forming a rectifying junction with the drift layer and the channel region(s); and

ohmic contacts on the gate and source regions and on the second major surface of the substrate;

a first electrical connection between the source ohmic contact of the lateral channel JFET and the gate ohmic contact of the vertical channel JFET; and

a second electrical connection between the drain ohmic contact of the lateral channel JFET and the source ohmic contact of the vertical channel JFET.

51. The integrated circuit of Claim 50, wherein for the lateral channel JFET: the buffer layer has a thickness of at least 0.1 μm ; the channel layer has a thickness of 0.3 to 1.5 μm ; the source, source/drain and drain regions each have a thickness of 0.2 to 1.5 μm ; and the first and second gate regions each have a thickness of 0.1 μm or more.

52. The integrated circuit of Claim 50, wherein for the lateral channel JFET: the buffer layer has a dopant concentration of 1×10^{15} to 1×10^{17} cm $^{-3}$; the channel layer has a dopant concentration of 5×10^{15} to 5×10^{17} cm $^{-3}$; the source, source/drain and drain regions each have a concentration of $> 5 \times 10^{18}$ cm $^{-3}$; and the first and second gate regions each have a dopant concentration of $> 5 \times 10^{18}$ cm $^{-3}$.

53. The integrated circuit of Claim 50, wherein for the lateral channel JFET the substrate is a semi-insulating substrate.

54. The integrated circuit of Claim 50, wherein for the vertical channel JFET: the drain layer has a thickness of 0.5 to 1 μ m; the drift layer has a thickness of 5 to 350 μ m; the channel region has a thickness of 0.2 to 1.5 μ m; the source region has a thickness of 0.2 to 1.5 μ m; and the gate region has a thickness of 0.1 μ m or more.

55. The integrated circuit of Claim 50, wherein for the vertical channel JFET: the drain layer has a dopant concentration of $> 5 \times 10^{18}$ cm $^{-3}$; the drift layer has a dopant concentration of 2×10^{14} to 2×10^{16} cm $^{-3}$; the channel region has a dopant concentration of 5×10^{15} to 5×10^{17} cm $^{-3}$; the source region has a dopant concentration of $> 5 \times 10^{18}$ cm $^{-3}$; and the gate region has a dopant concentration of $> 5 \times 10^{18}$ cm $^{-3}$.

56. The integrated circuit of Claim 50, wherein for the vertical channel JFET the substrate is an n-type substrate having a dopant concentration of $> 1 \times 10^{18}$ cm.

57. The integrated circuit of Claim 50, wherein for the lateral channel JFET the semiconductor material of each of the buffer layer, drain region, source region, gate region and channel layer has an E_G of at least 2 eV.

58. The integrated circuit of Claim 57, wherein the semiconductor material is SiC or a Group III nitride compound semiconductor material.

59. The integrated circuit of Claim 50, wherein, for the vertical channel JFET, the semiconductor material of each of the drain layer, drift layer, channel region, source region and gate region has an E_G of at least 2 eV.

60. The integrated circuit of Claim 59, wherein the semiconductor material is SiC or a Group III nitride compound semiconductor material.

61. A monolithic integrated circuit comprising a lateral junction field effect transistor and a vertical junction field effect transistor;
the lateral junction field effect transistor comprising:
a buffer layer of a p-type semiconductor material formed in a portion of a first major surface of a drift layer;
a channel layer of an n-type semiconductor material on and non-coextensive with the buffer layer such that a portion of the buffer layer is exposed;
discrete source and drain regions of an n-type semiconductor material in spaced relation on the channel layer;
a gate region of a p-type semiconductor material formed in the channel layer between the source and drain regions and forming a rectifying junction with the channel layer;

ohmic contacts on the source region, the gate region, the drain region and on the exposed portion of the buffer layer;

the vertical junction field effect transistor comprising:

a channel layer of an n-type semiconductor material on the first major surface of the drift layer laterally spaced from the buffer layer;

one or more discrete source regions of an n-type semiconductor material in spaced relation on the channel layer;

a gate region of a p-type semiconductor material formed in the channel layer adjacent the one or more source regions and forming a rectifying junction with the channel layer; and

ohmic contacts on the gate and source regions;

wherein the drift layer is on a drain layer of an n-type semiconductor material which is on a first major surface of a substrate; and wherein an electrical contact is on a second major surface of the substrate opposite the first major surface of the substrate.

62. The integrated circuit of Claim 61, wherein the drain layer has a thickness of 0.5 to 1 μm and the drift layer has a thickness of 5 to 350 μm .

63. The integrated circuit of Claim 61, wherein the drain layer has a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$ and the drift layer has a dopant concentration of 2×10^{14} to $2 \times 10^{16} \text{ cm}^{-3}$.

64. The integrated circuit of Claim 61, wherein the substrate is an n-type substrate having a dopant concentration of $> 1 \times 10^{18} \text{ cm}^{-3}$.

65. The integrated circuit of Claim 61, wherein for the lateral junction field effect transistor the channel region has a thickness of 0.2 to 1.5 μm ; the source and drain regions each have a thickness of 0.2 to 1.5 μm ; and the gate region and buffer layer each have a thickness of 0.1 μm or more.

66. The integrated circuit of Claim 1, wherein for the lateral junction field effect transistor the channel region has a dopant concentration of 5×10^{15} to 5×10^{17} cm^{-3} ; the source region has a dopant concentration of $> 5 \times 10^{18}$ cm^{-3} ; and the gate region and buffer layer each have a dopant concentration of $> 5 \times 10^{18}$ cm^{-3} .

67. The integrated circuit of Claim 61, further comprising:

a first electrical connection between the source contact of the lateral channel JFET and the gate contact of the vertical channel JFET;

a second electrical connection between the gate and buffer layer contacts of the lateral channel JFET; and

a third electrical connection between the drain contact of the lateral channel JFET and the source contact of the vertical channel JFET.

68. The integrated circuit of Claim 61, further comprising one or more rings of p-type semiconductor material formed in the drift layer and circumscribing the lateral junction field effect transistor.

69. The integrated circuit of Claim 61, further comprising one or more rings of p-type semiconductor material formed in the drift layer and circumscribing the vertical junction field effect transistor.

70. The integrated circuit of Claim 61, wherein for the lateral junction field effect transistor the semiconductor material of each of the buffer layer, drain region, source region, gate region and channel layer has an E_G of at least 2 eV.

71. The integrated circuit of Claim 70, wherein for the lateral junction field effect transistor the semiconductor material of each of the buffer layer, drain region, source region, gate region and channel layer is SiC or a Group III nitride compound semiconductor material.

72. The integrated circuit of Claim 61, wherein, for the vertical junction field effect transistor, the semiconductor material of each of the channel layer, source region and gate region has an E_G of at least 2 eV.

73. The integrated circuit of Claim 72, wherein for the vertical junction field effect transistor, the semiconductor material of each of the channel layer, source region and gate region is SiC or a Group III nitride compound semiconductor material.

74. The integrated circuit of Claim 61, wherein the semiconductor material of each of the drift layer and the drain layer has an E_G of at least 2 eV.

75. The integrated circuit of Claim 74, wherein the semiconductor material of each of the drift layer and the drain layer is SiC or a Group III nitride compound semiconductor material.

76. A monolithic integrated circuit comprising a lateral junction field effect transistor and a vertical junction field effect transistor; the lateral junction field effect transistor comprising:

a buffer layer of a p-type semiconductor material formed in a portion of a first major surface of a drift layer;

a channel layer of an n-type semiconductor material on and non-coextensive with the buffer layer such that a portion of the buffer layer is exposed;

discrete source and drain regions each of an n-type semiconductor material in spaced relation on the channel layer;

a metal layer on the channel layer between the source and drain regions forming a metal-semiconductor rectifying junction with the channel layer;

ohmic contacts on the source region, the drain region and on the exposed portion of the buffer layer;

the vertical junction field effect transistor comprising:

one or more raised regions on the first major surface of the drift layer laterally spaced from the buffer layer each comprising a channel region of an n-type semiconductor material on the first major surface of the drift layer and spaced from the buffer layer of the lateral junction field effect transistor and a source region of an n-type semiconductor material on the channel region;

a metal layer on the drift layer adjacent to the one or more raised regions forming a metal-semiconductor rectifying junction with the drift layer and the channel region(s); and

an ohmic contact on the source region;

wherein the drift layer is on a layer of n-type semiconductor material which is on a first major surface of a substrate; and wherein an electrical contact is on a

second major surface of the substrate opposite the first major surface of the substrate.

77. The integrated circuit of Claim 76, wherein the drain layer has a thickness of 0.5 to 1 μm and the drift layer has a thickness of 5 to 350 μm .

78. The integrated circuit of Claim 76, wherein the drain layer has a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$ and the drift layer has a dopant concentration of 2×10^{14} to $2 \times 10^{16} \text{ cm}^{-3}$.

79. The integrated circuit of Claim 76, wherein the substrate is an n-type substrate having a dopant concentration of $> 1 \times 10^{18} \text{ cm}^{-3}$.

80. The integrated circuit of Claim 76, wherein for the lateral junction field effect transistor the channel region has a thickness of 0.2 to 1.5 μm ; the source and drain regions each have a thickness of 0.2 to 1.5 μm ; and the gate region and buffer layer each have a thickness of 0.1 μm or more.

81. The integrated circuit of Claim 76, wherein for the lateral junction field effect transistor the channel region has a dopant concentration of 5×10^{15} to $5 \times 10^{17} \text{ cm}^{-3}$; the source region has a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$; and the gate region and buffer layer each have a dopant concentration of $> 5 \times 10^{18} \text{ cm}^{-3}$.

82. The integrated circuit of Claim 76, further comprising:
a first electrical connection between the source contact of the lateral junction field effect transistor and the metal layer of the vertical junction field effect transistor ;

a second electrical connection between the metal layer and buffer contacts of the lateral junction field effect transistor; and
a third electrical connection between the drain contact of the lateral junction field effect transistor and the source contact of the vertical junction field effect transistor.

83. The integrated circuit of Claim 76, further comprising one or more rings of p-type semiconductor material formed in the drift layer and circumscribing the lateral channel junction field effect transistor.

84. The integrated circuit of Claim 76, further comprising one or more rings of p-type semiconductor material formed in the drift layer and circumscribing the vertical channel junction field effect transistor.

85. The integrated circuit of Claim 76, wherein for the lateral junction field effect transistor the semiconductor material of each of the buffer layer, drain region, source region, gate region and channel layer has an E_G of at least 2 eV.

86. The integrated circuit of Claim 85, wherein for the lateral junction field effect transistor the semiconductor material of each of the buffer layer, drain region, source region, gate region and channel layer is SiC or a Group III nitride compound semiconductor material.

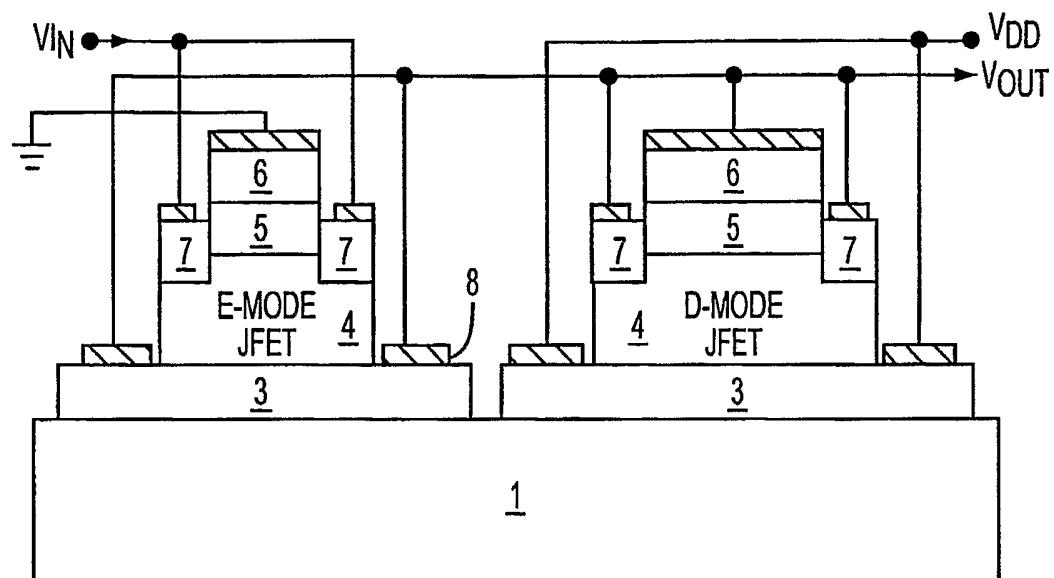
87. The integrated circuit of Claim 76, wherein, for the vertical junction field effect transistor, the semiconductor material of each of the channel layer, source region and gate region has an E_G of at least 2 eV.

88. The integrated circuit of Claim 87, wherein for the vertical junction field effect transistor, the semiconductor material of each of the channel layer, source region and gate region is SiC or a Group III nitride compound semiconductor material.

89. The integrated circuit of Claim 76, wherein the semiconductor material of each of the drift layer and the drain layer has an E_G of at least 2 eV.

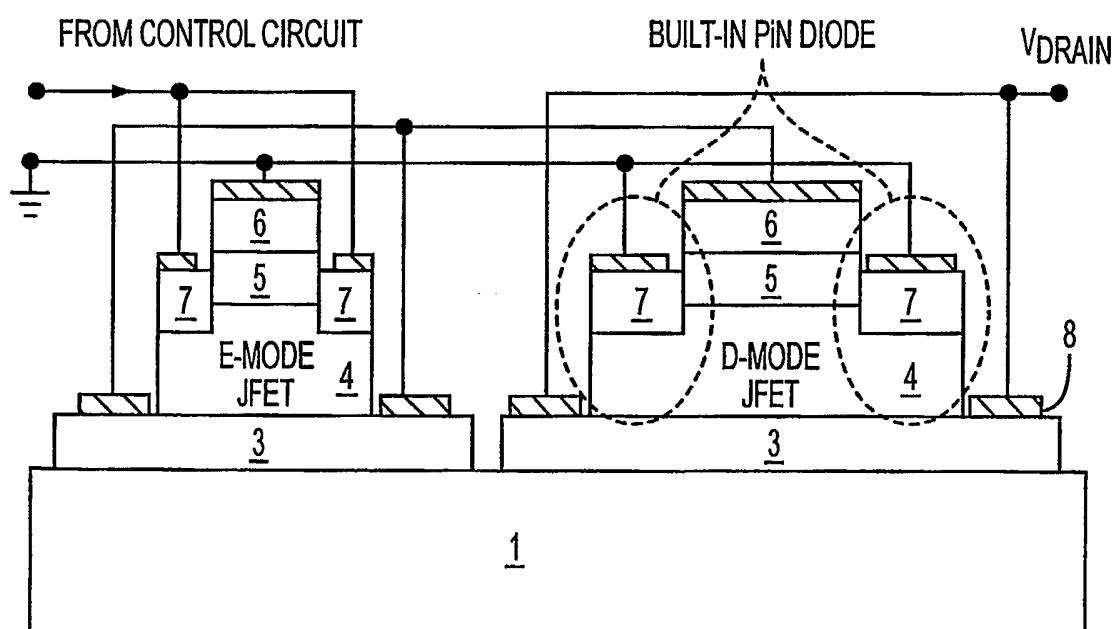
90. The integrated circuit of Claim 89, wherein the semiconductor material of each of the drift layer and the drain layer is SiC or a Group III nitride compound semiconductor material.

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VERTICAL CHANNEL JFET IC CHIP

FIG. 1



VERTICAL CHANNEL JFET IC CHIP

FIG. 2

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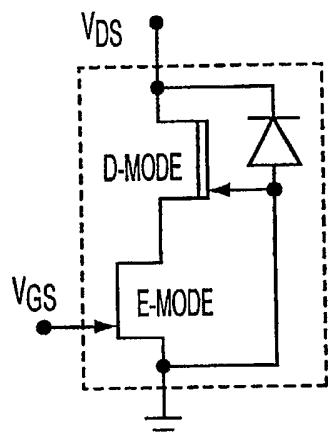


FIG. 3A

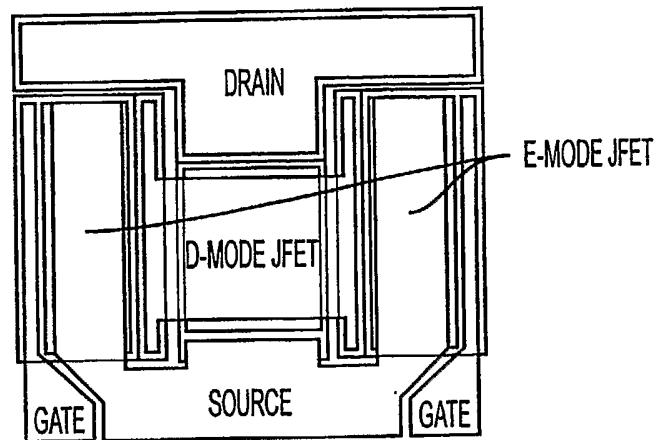


FIG. 3B

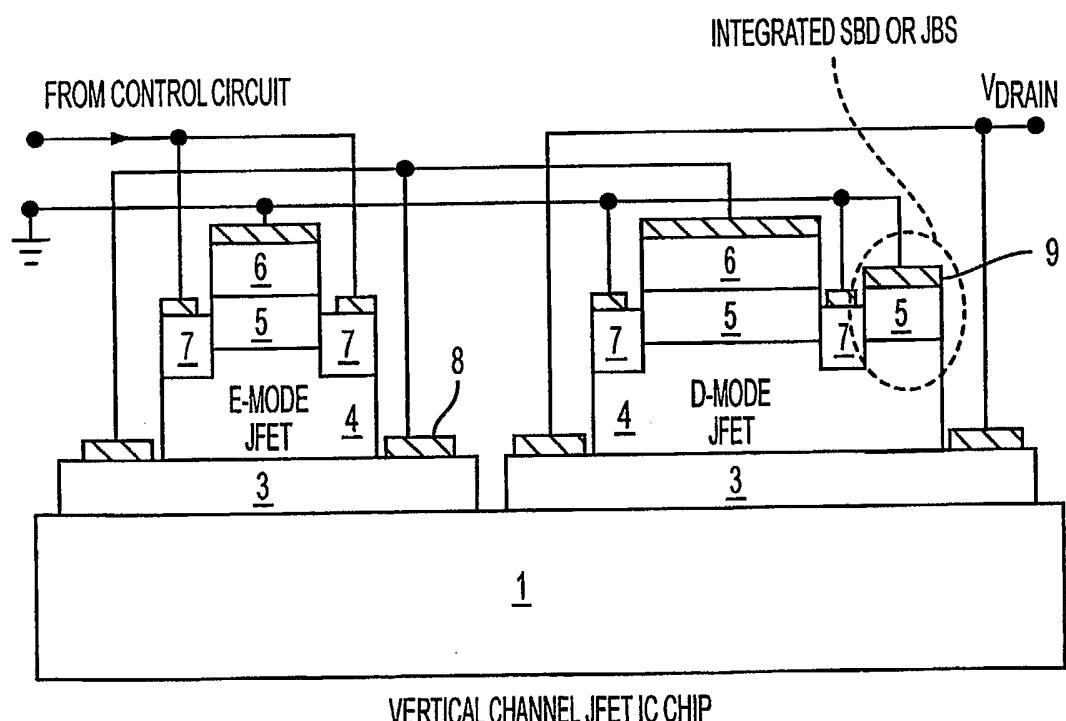


FIG. 4

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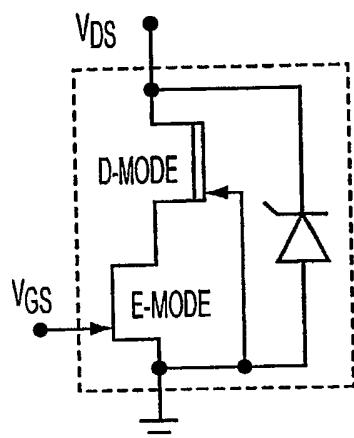


FIG. 5A

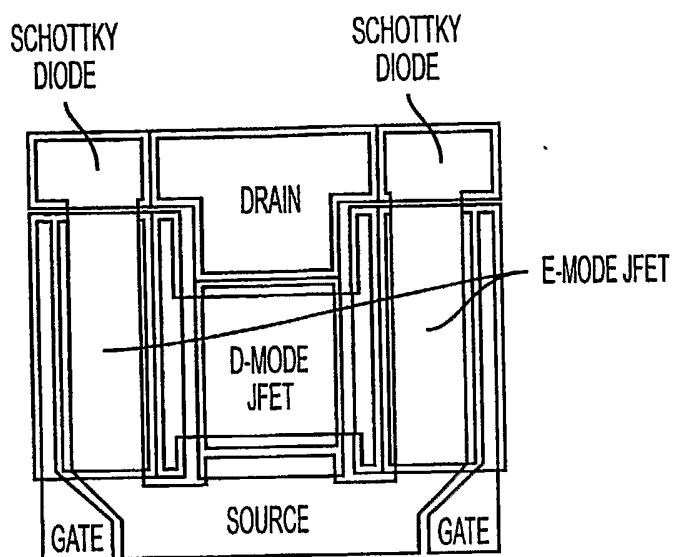


FIG. 5B

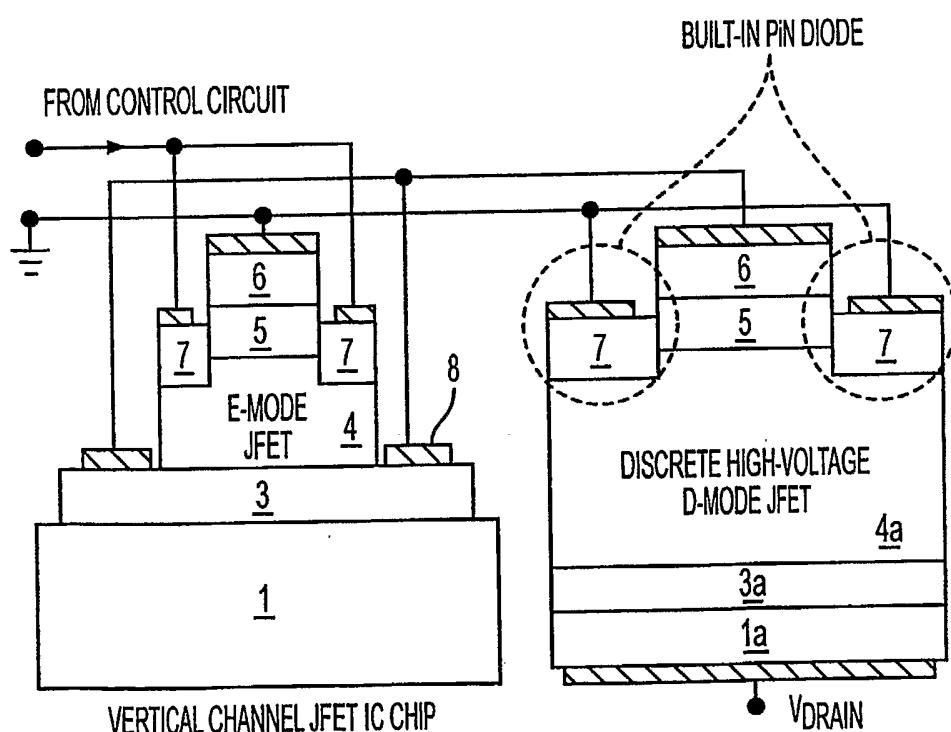


FIG. 6

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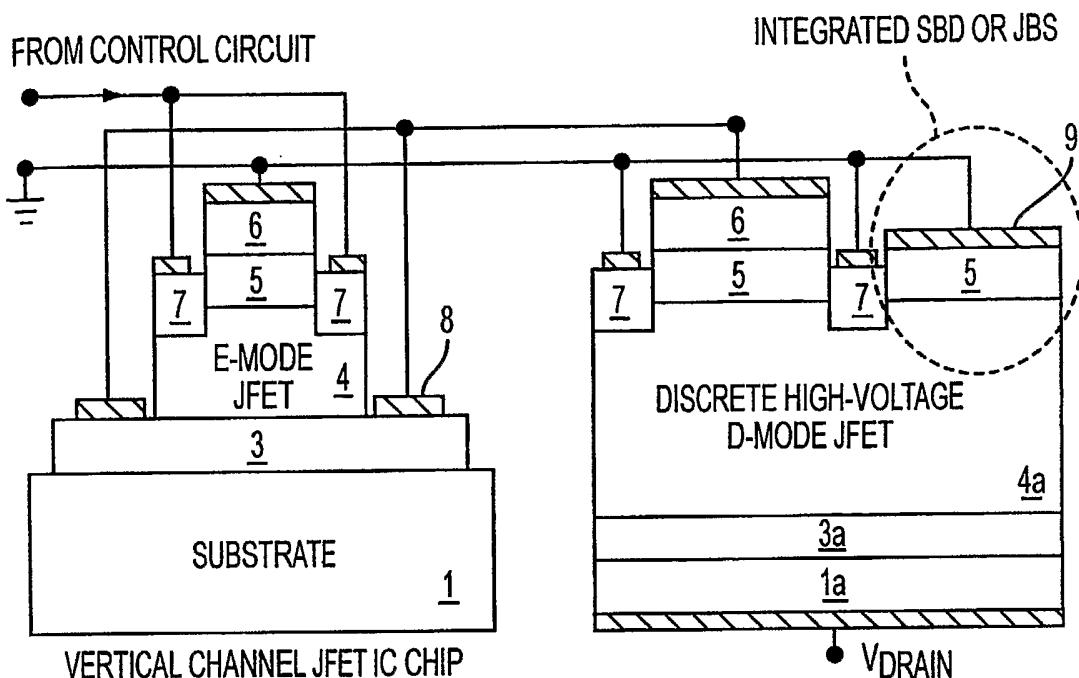


FIG. 7

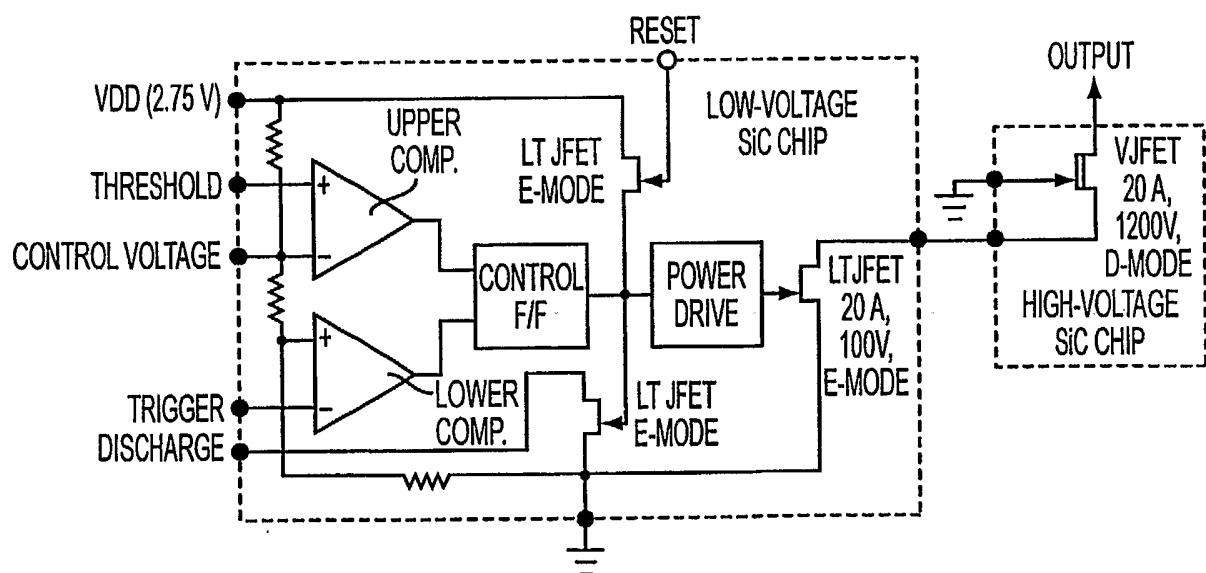
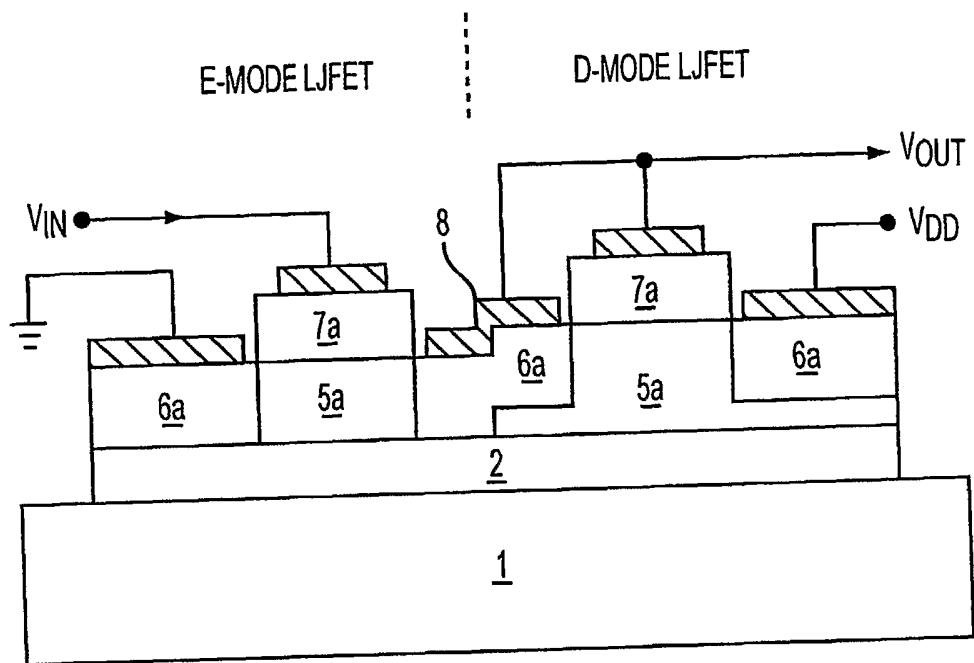


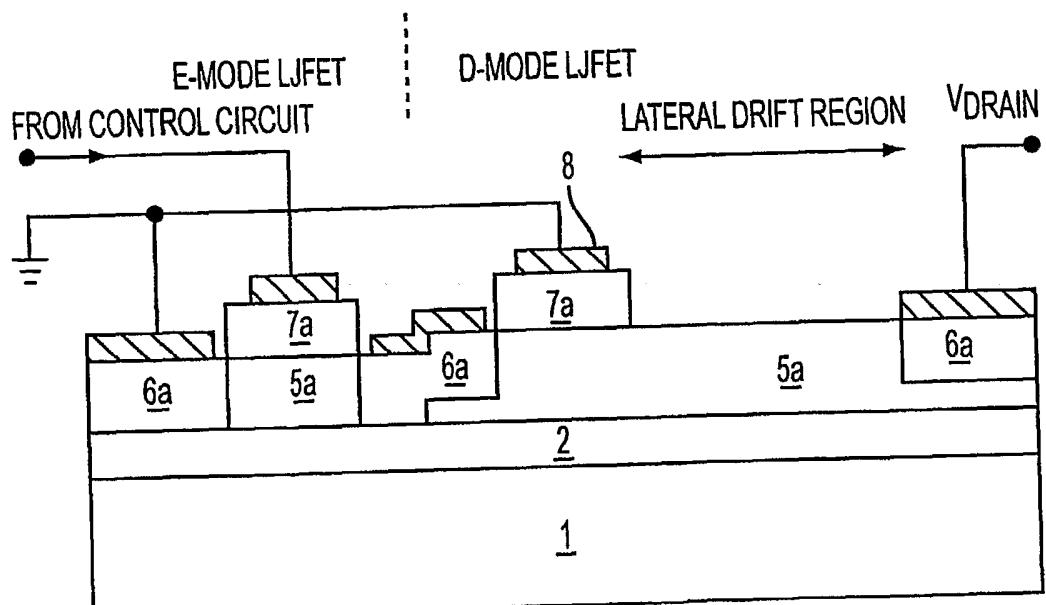
FIG. 8

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LATERAL CHANNEL JFET IC CHIP

FIG. 9



LATERAL CHANNEL JFET IC CHIP

FIG. 10

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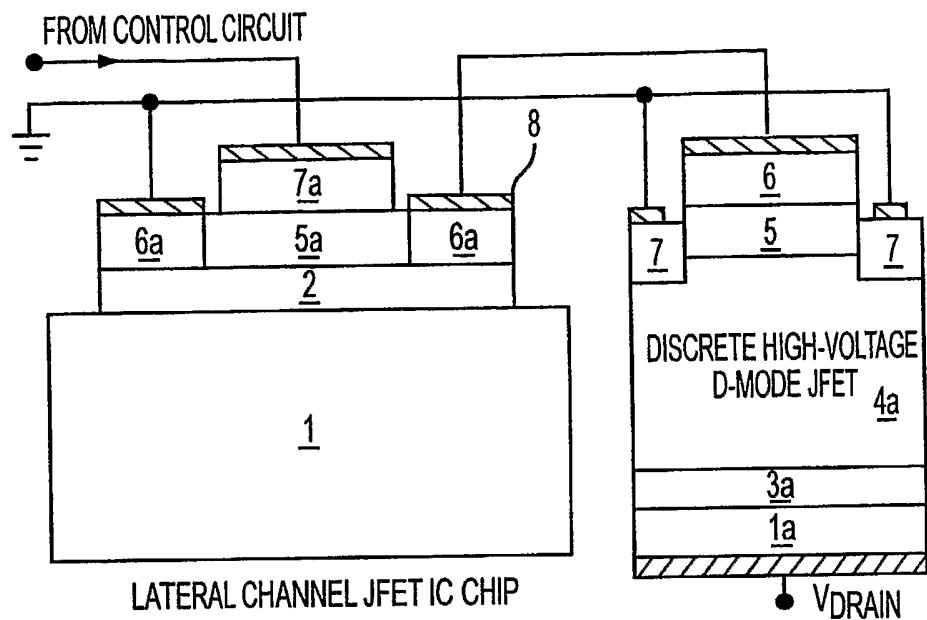


FIG. 11

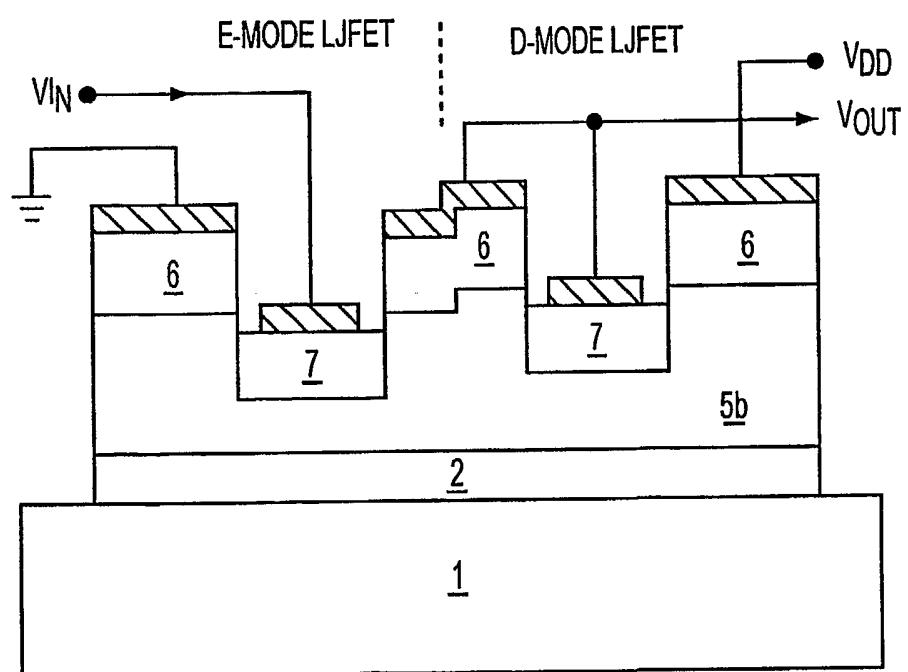


FIG. 12

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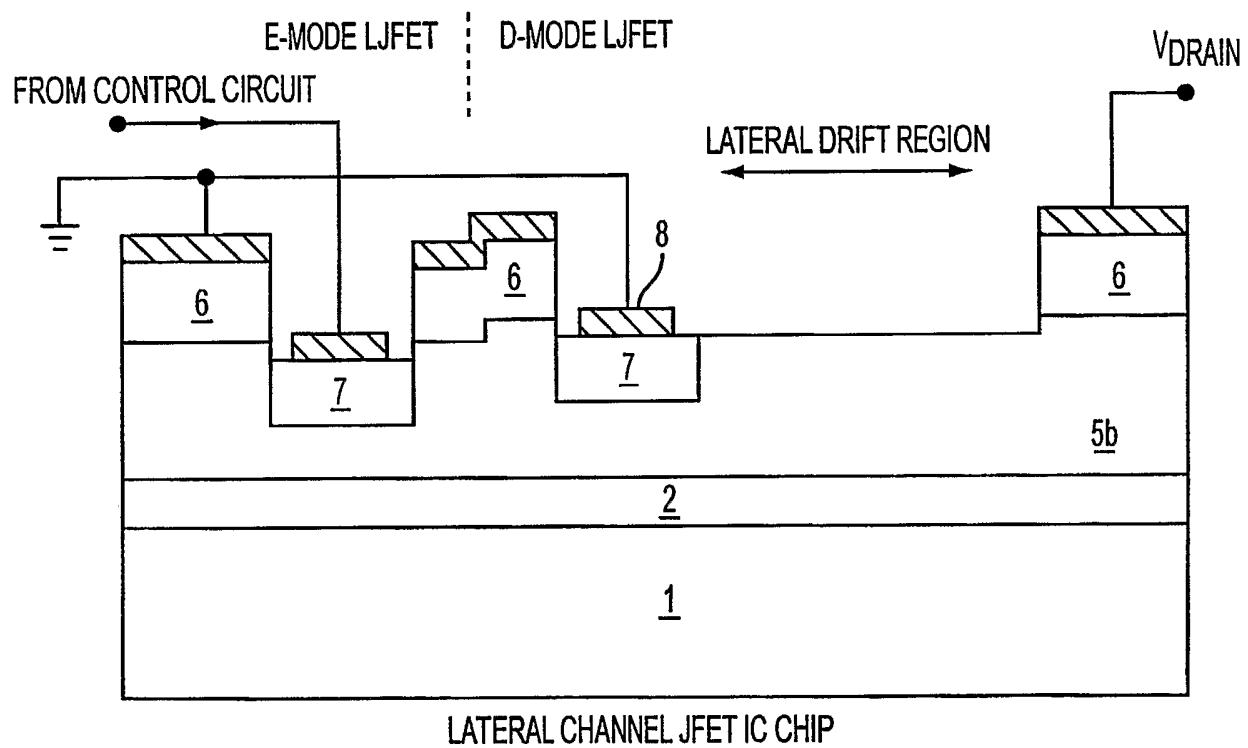


FIG. 13

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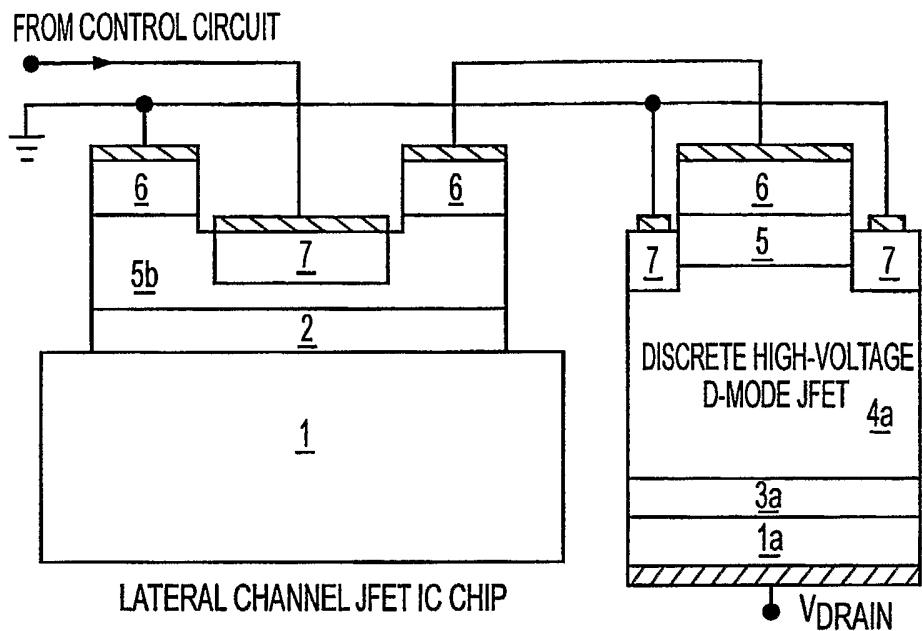


FIG. 14

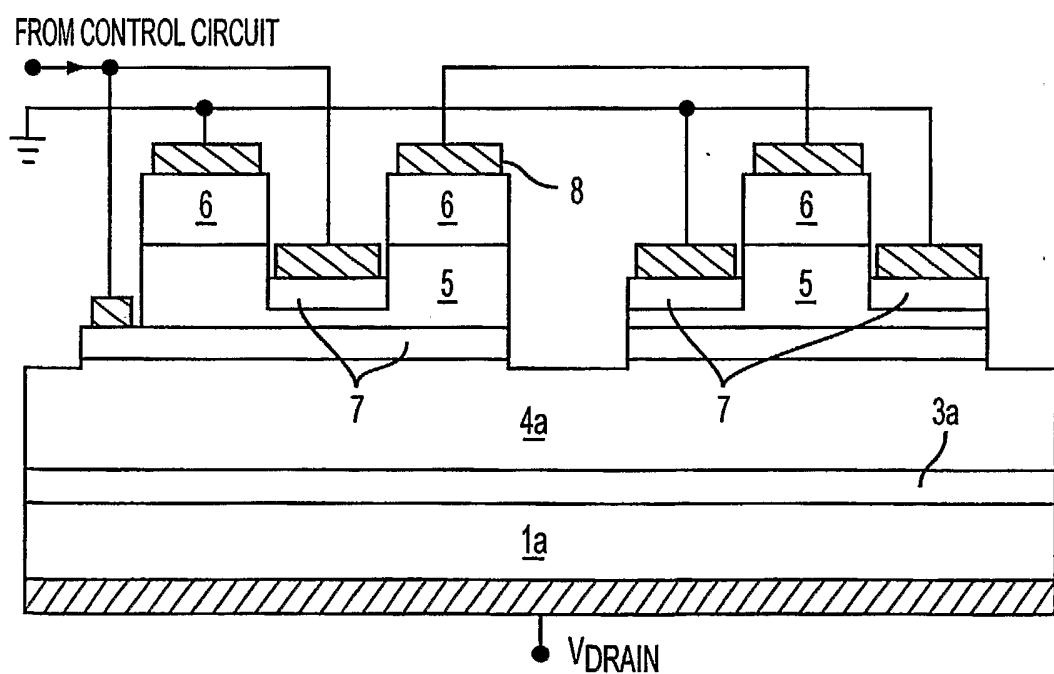


FIG. 15

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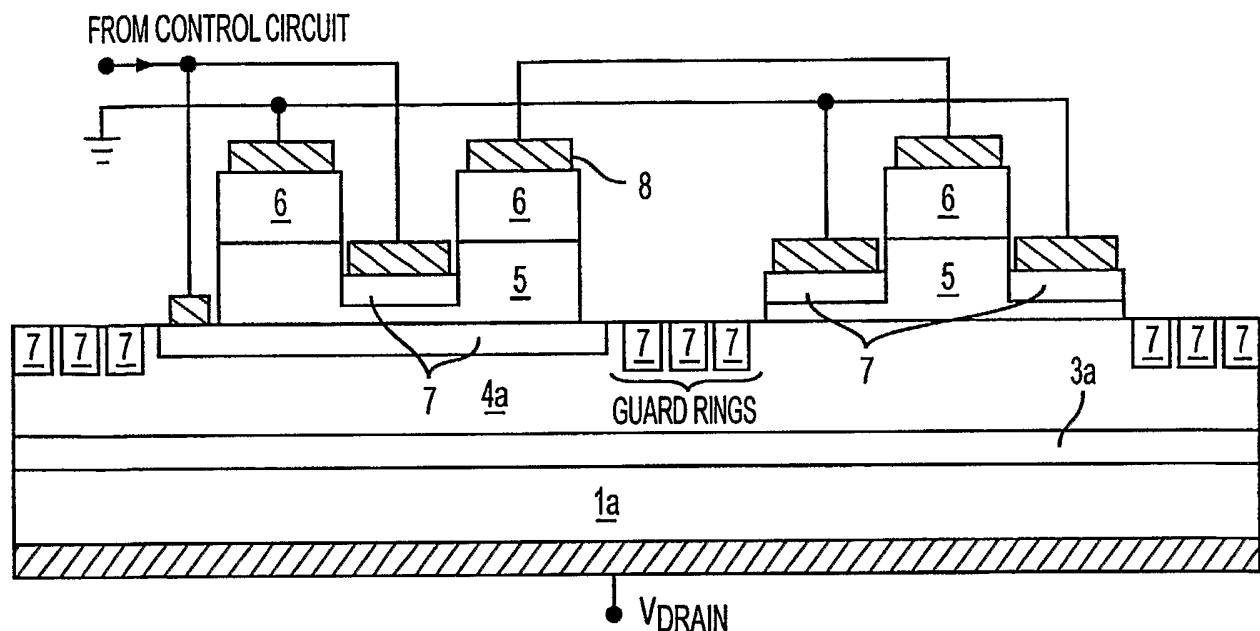


FIG. 16

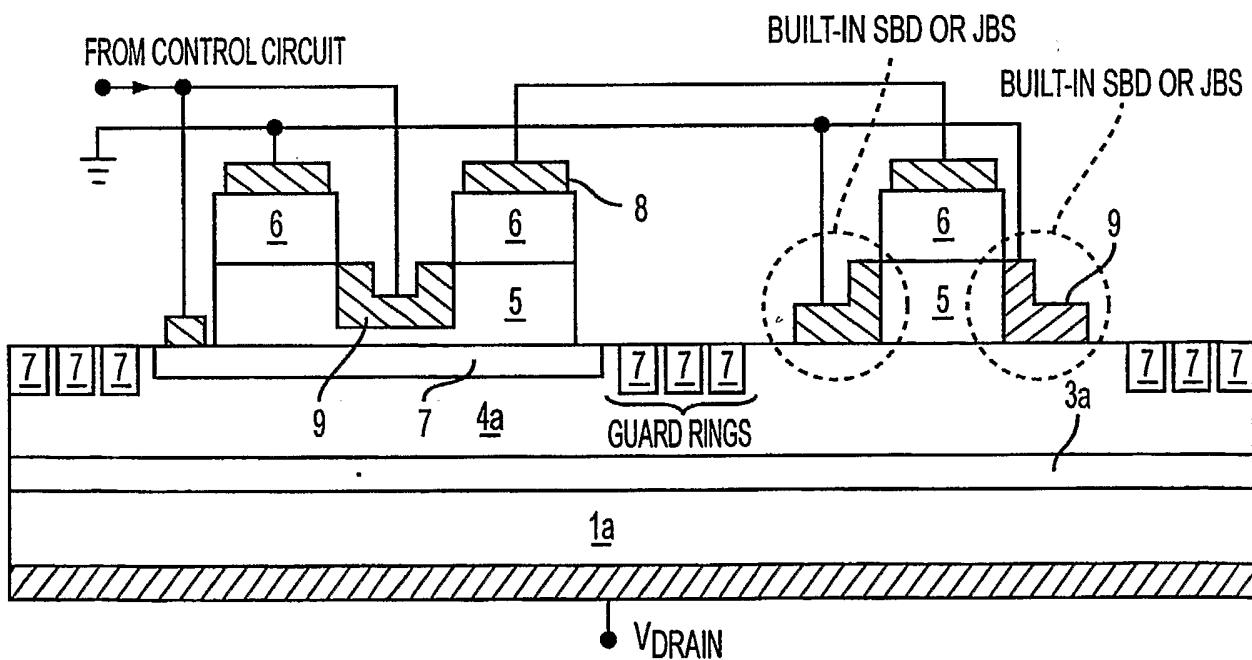


FIG. 17

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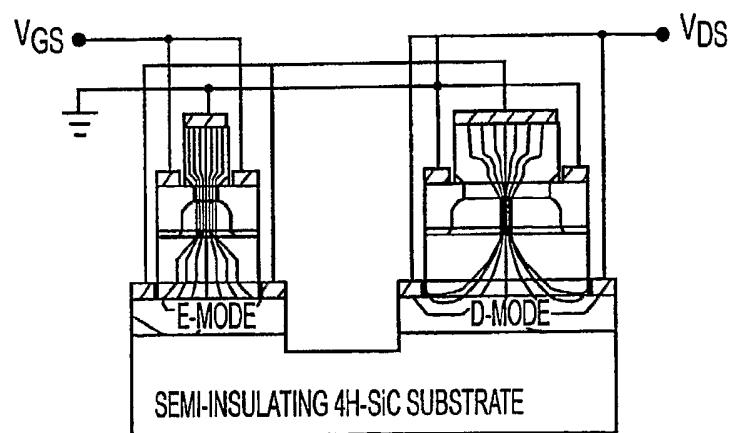
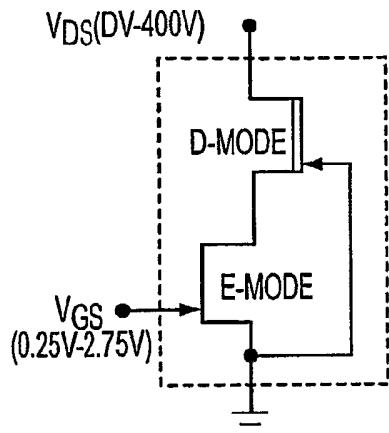


FIG. 18A

FIG. 18B

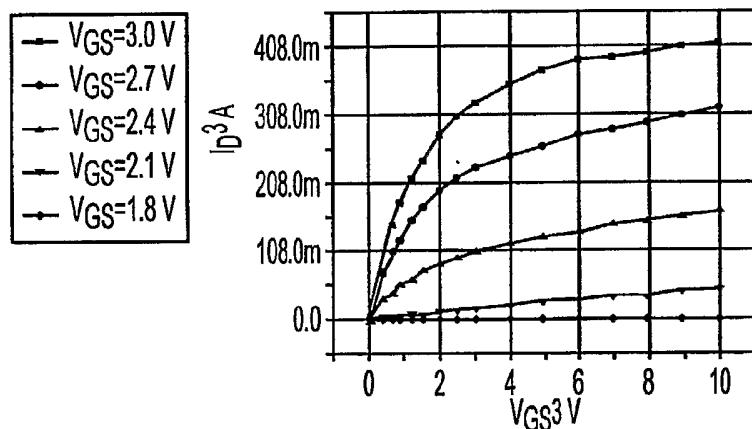
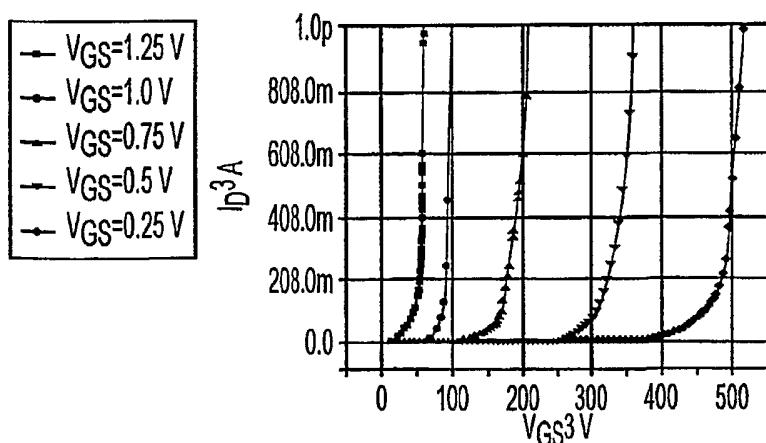


FIG. 18C



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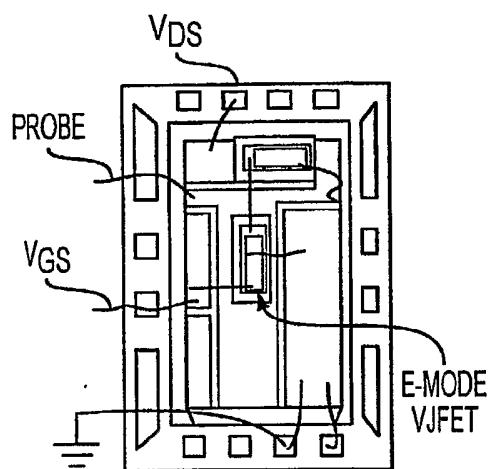


FIG. 19A

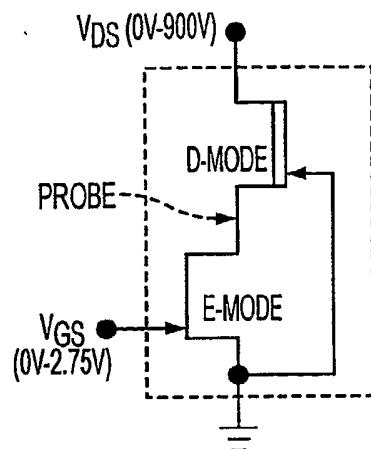


FIG. 19B

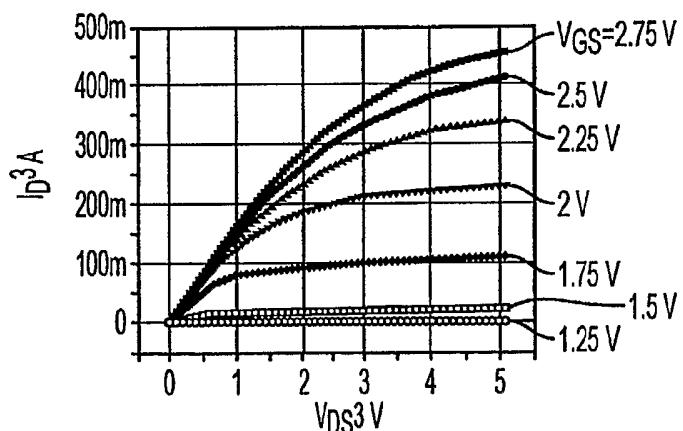
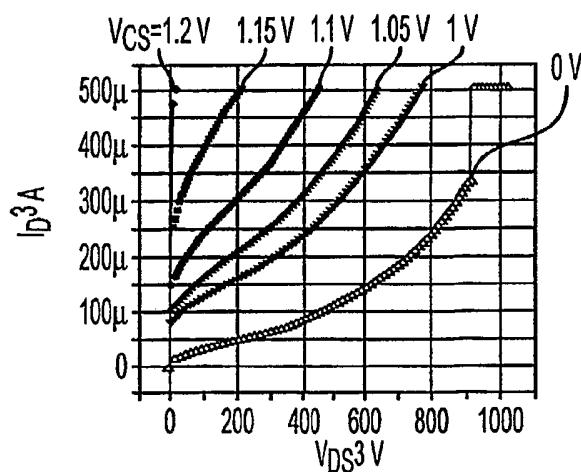


FIG. 19C



SUBSTITUTE FIG. 19D (RULE 26)

SUBSTITUTE SHEET (RULE 26)

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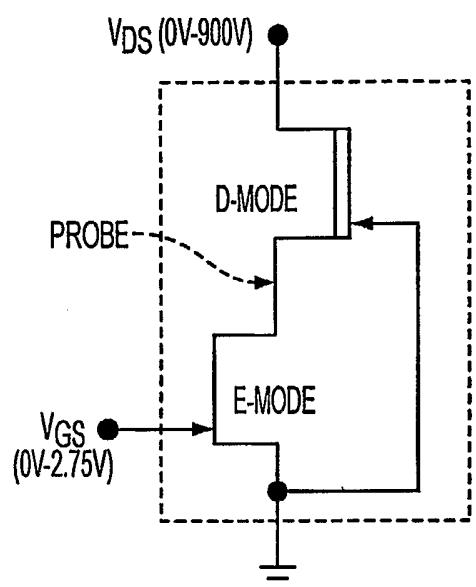


FIG. 20A

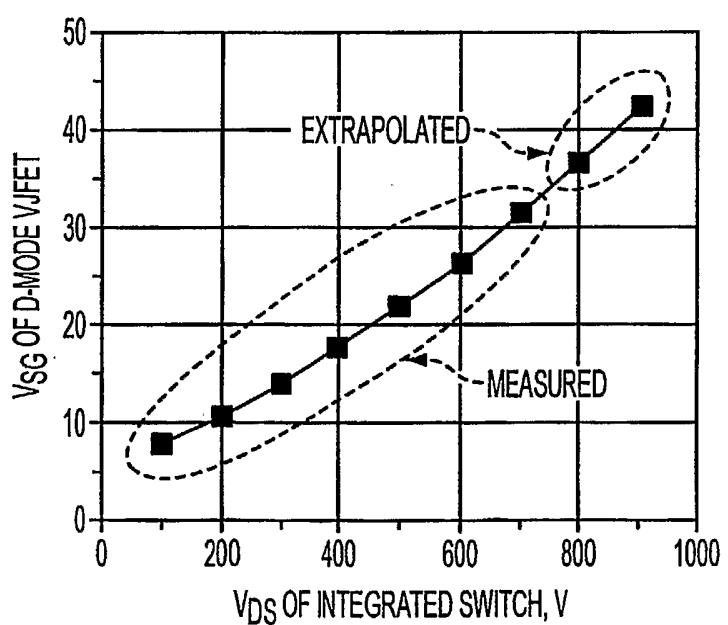


FIG. 20B

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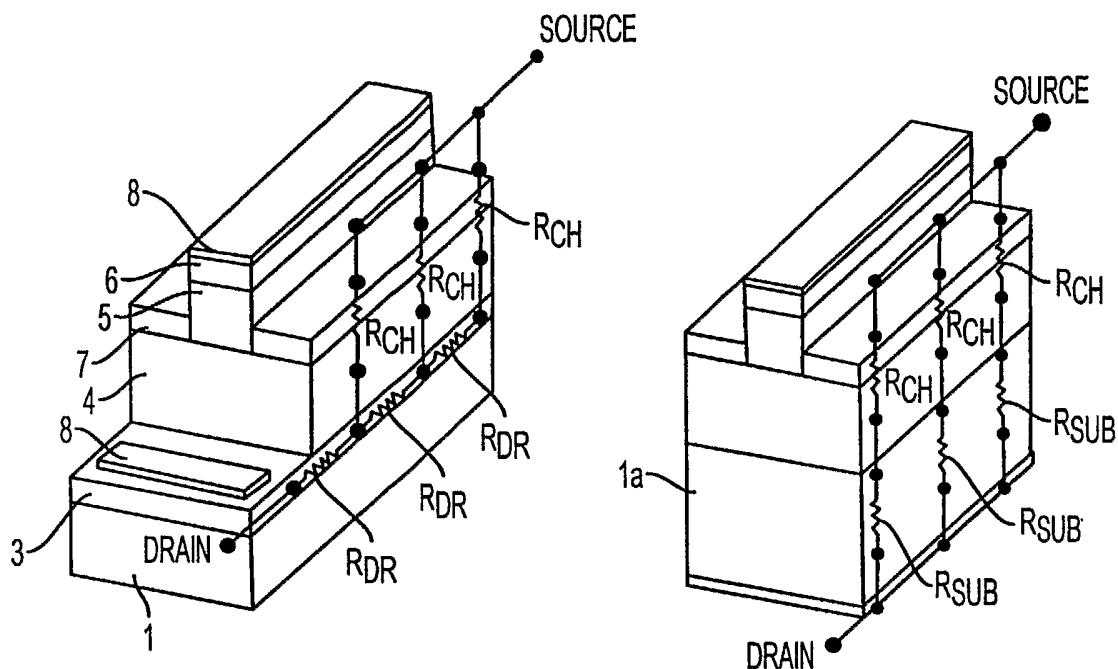


FIG. 21A

FIG. 21B

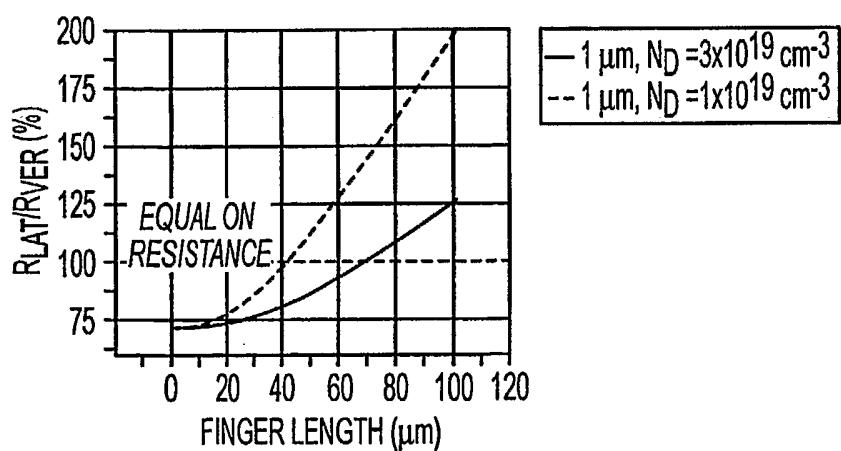


FIG. 21C

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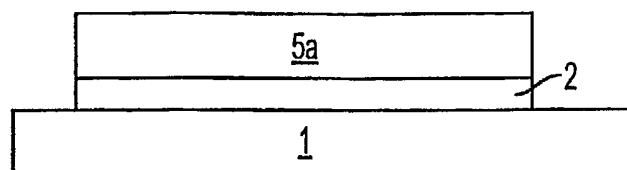


FIG. 22A

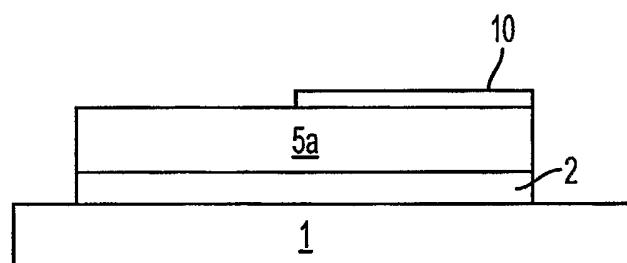


FIG. 22B

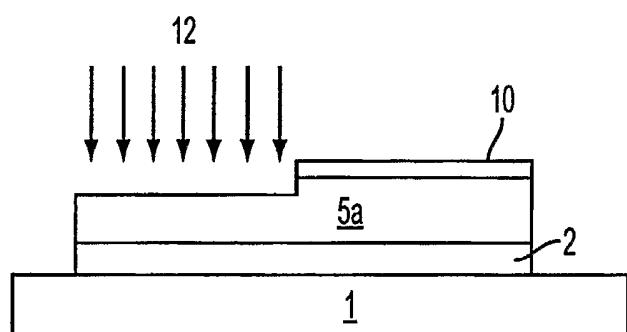


FIG. 22C

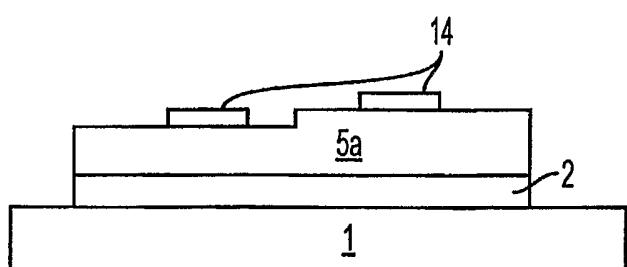


FIG. 22D

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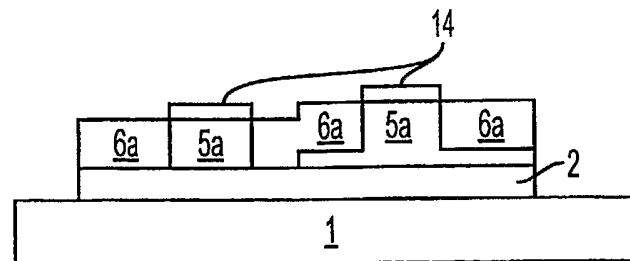


FIG. 22E

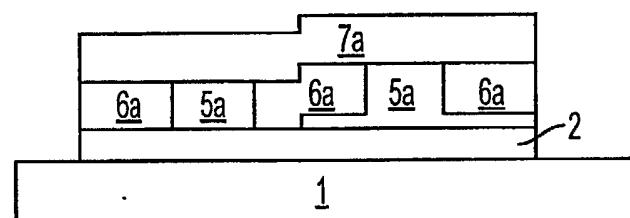


FIG. 22F

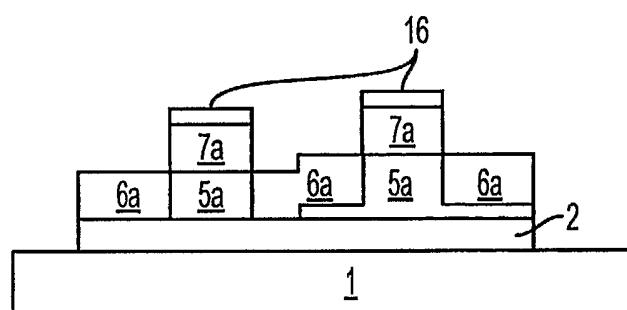


FIG. 22G

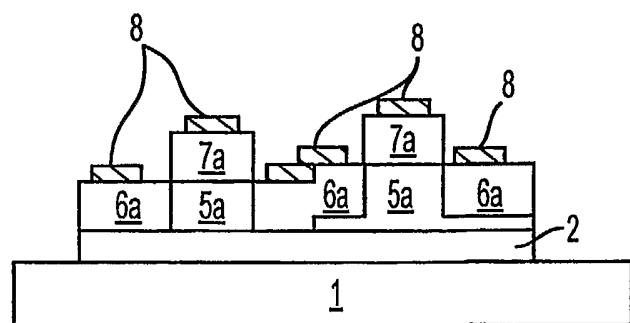


FIG. 22H

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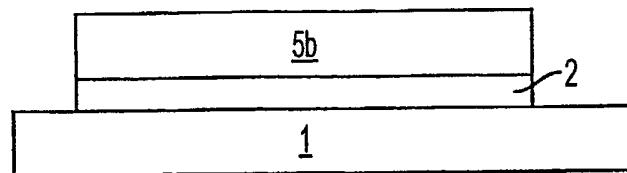


FIG. 23A

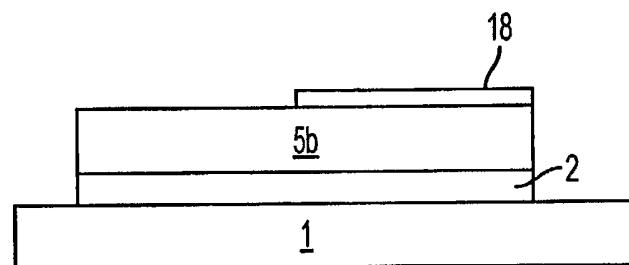


FIG. 23B

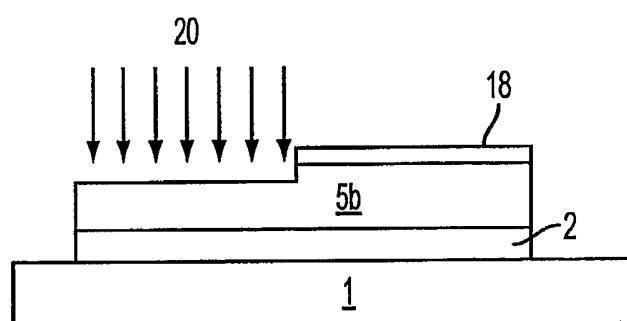


FIG. 23C

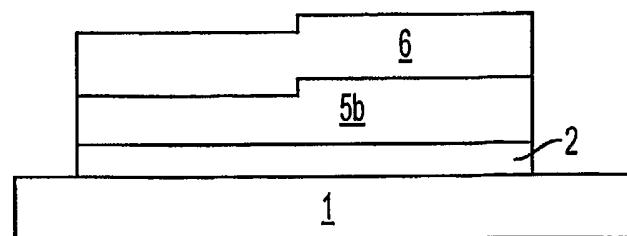


FIG. 23D

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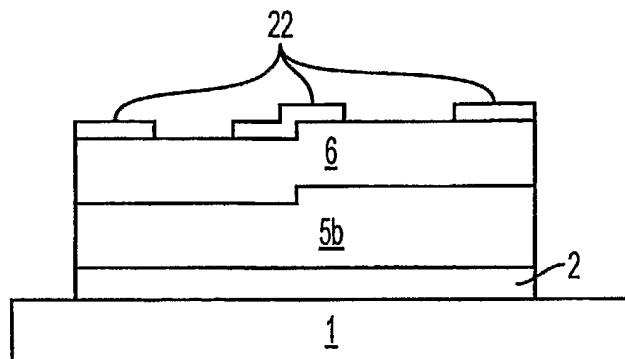


FIG. 23E

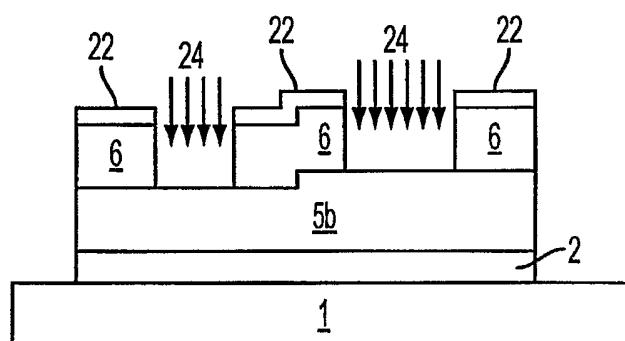


FIG. 23F

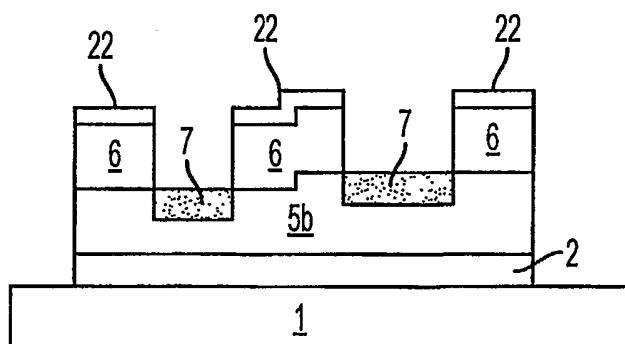


FIG. 23G

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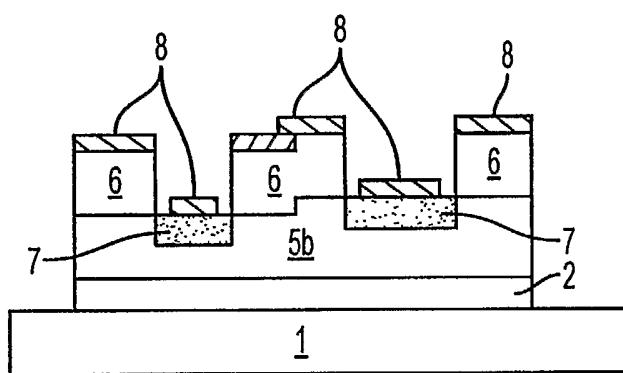


FIG. 23H

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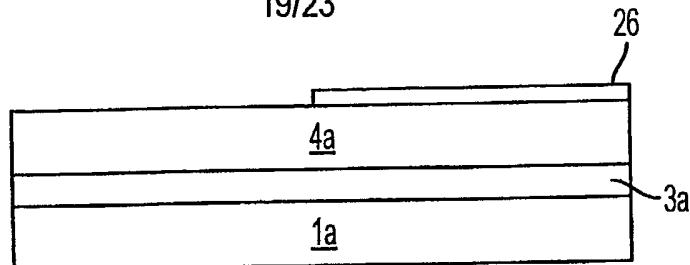


FIG. 24A

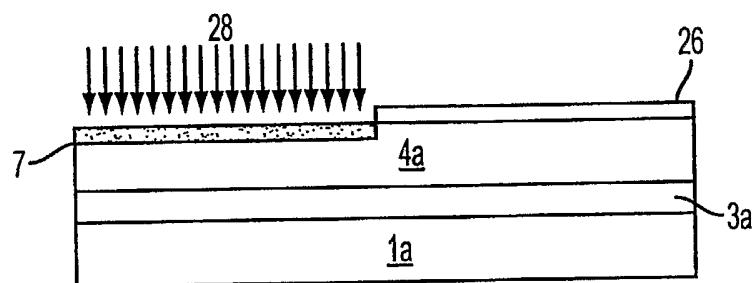


FIG. 24B

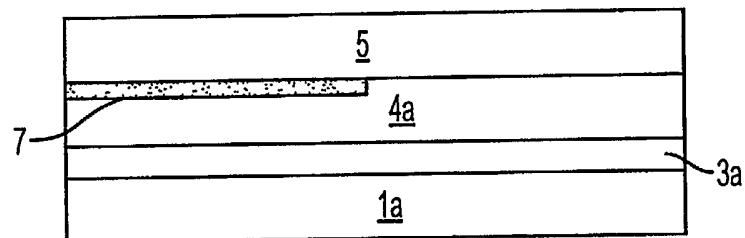


FIG. 24C

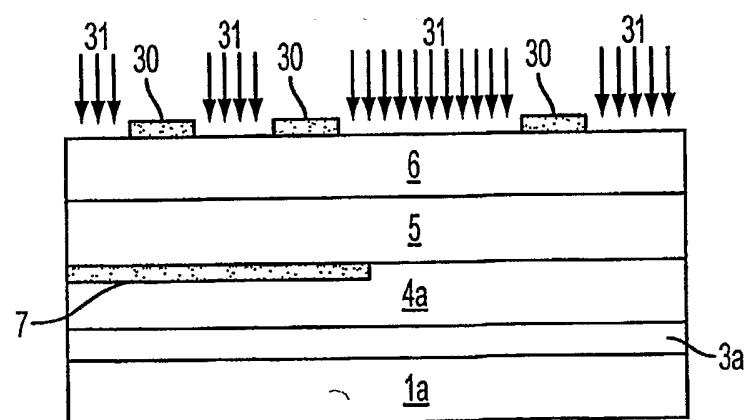


FIG. 24D

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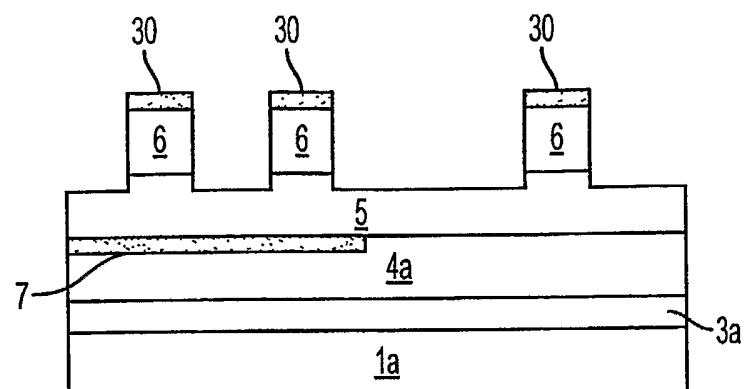


FIG. 24E

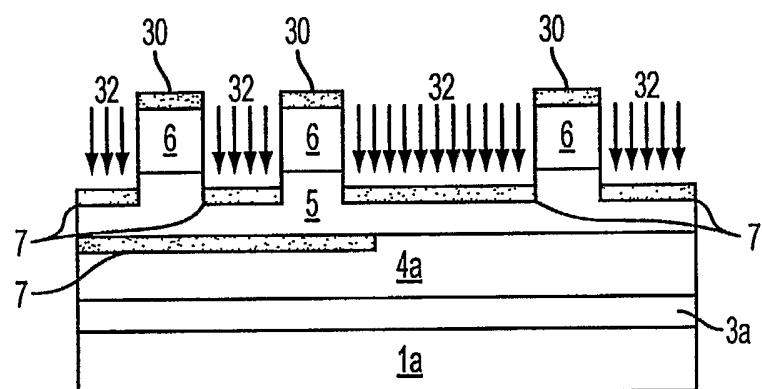


FIG. 24F

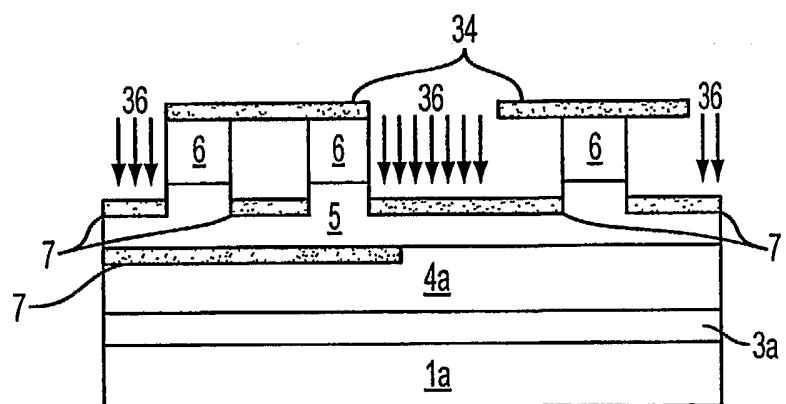


FIG. 24G

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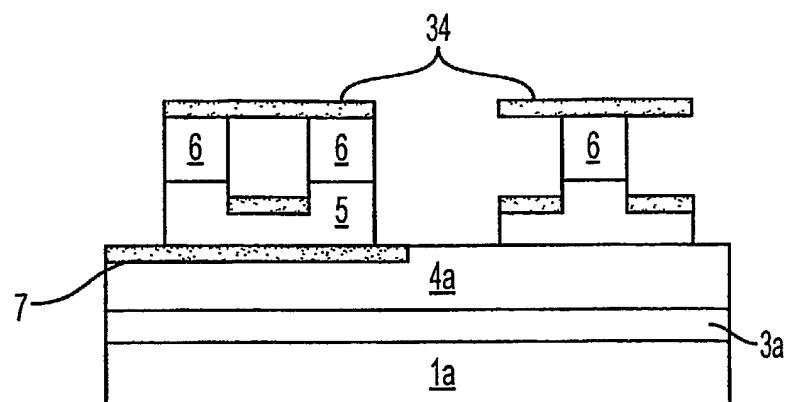


FIG. 24H

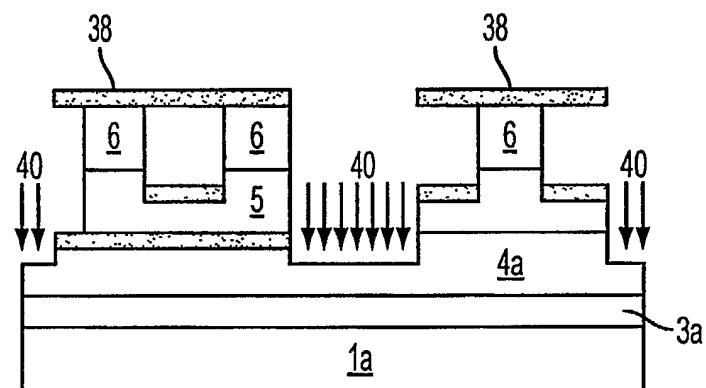


FIG. 24I

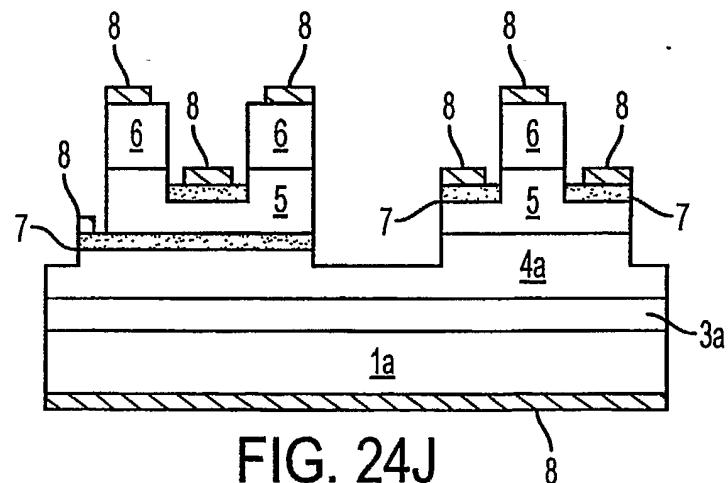


FIG. 24J

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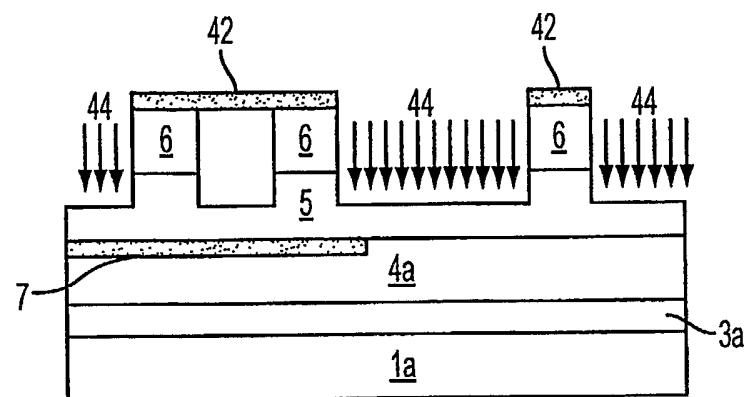


FIG. 25A

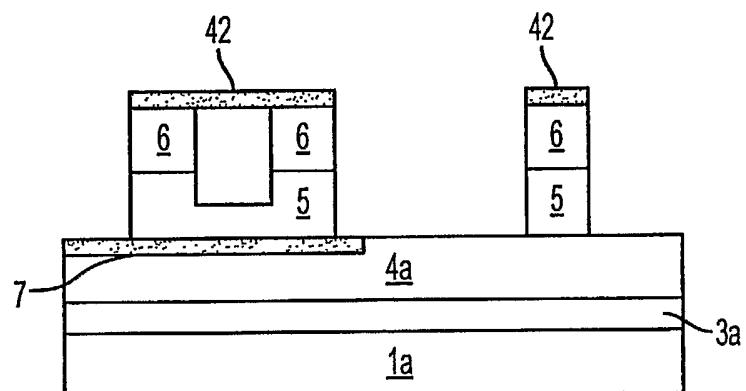


FIG. 25B

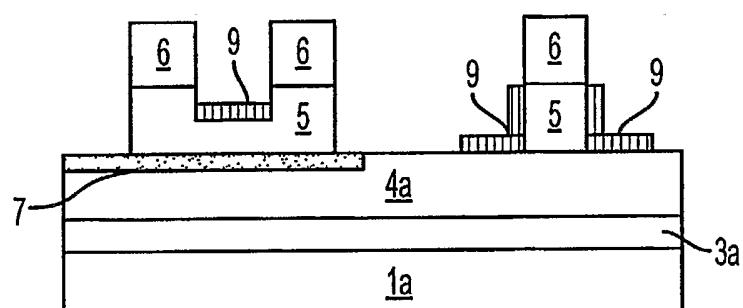


FIG. 25C

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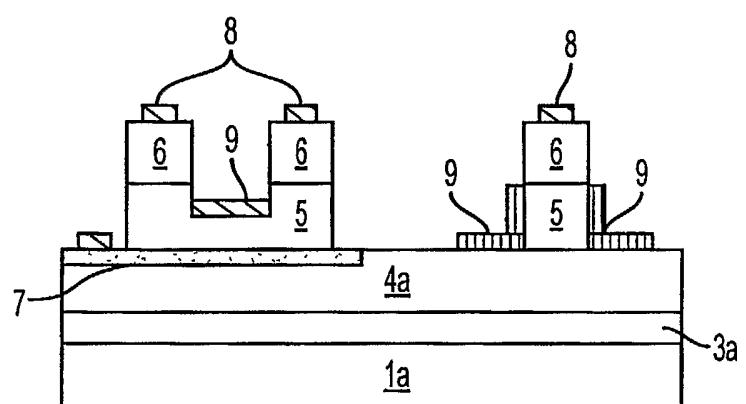


FIG. 25D