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(54) **METHOD OF FORMING TRENCH GATE FIELD EFFECT TRANSISTOR WITH RECESSED MESAS**

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See application file for complete search history.

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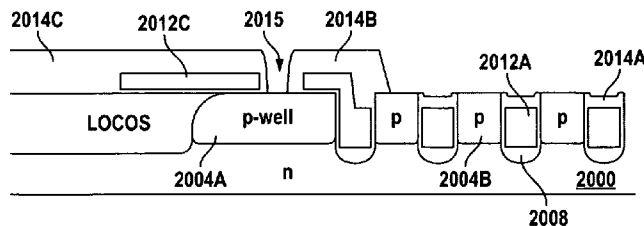
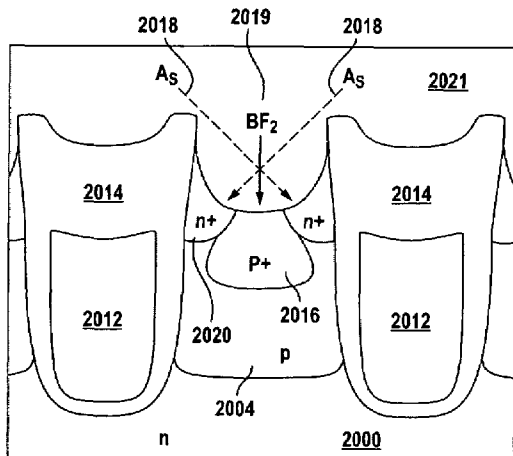
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(57) **ABSTRACT**

A monolithically integrated field effect transistor and Schottky diode includes gate trenches extending into a semiconductor region. Source regions having a substantially triangular shape flank each side of the gate trenches. A contact opening extends into the semiconductor region between adjacent gate trenches. A conductor layer fills the contact opening to electrically contact: (a) the source regions along at least a portion of a slanted sidewall of each source region, and (b) the semiconductor region along a bottom portion of the contact opening, wherein the conductor layer forms a Schottky contact with the semiconductor region.

13 Claims, 29 Drawing Sheets



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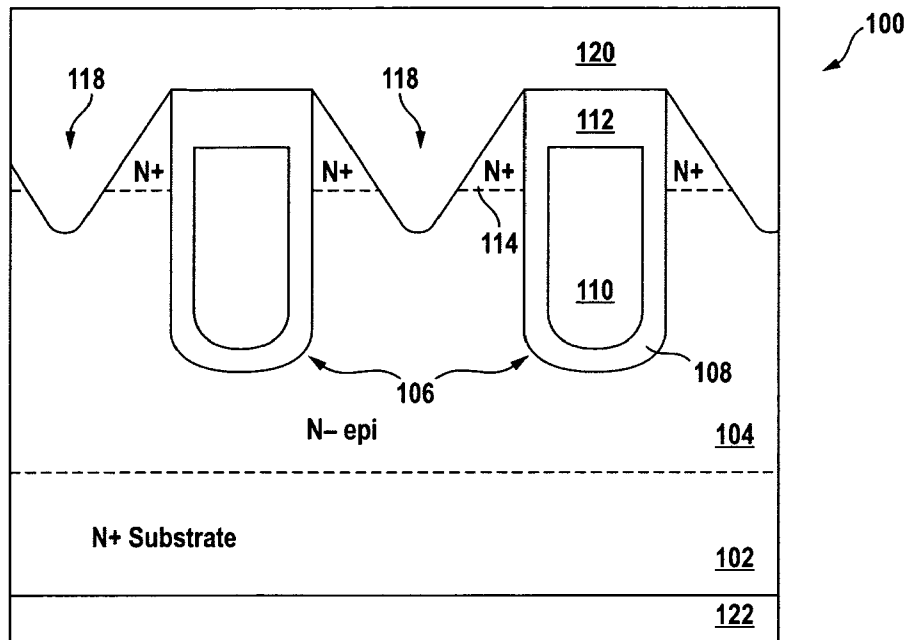


FIG. 1

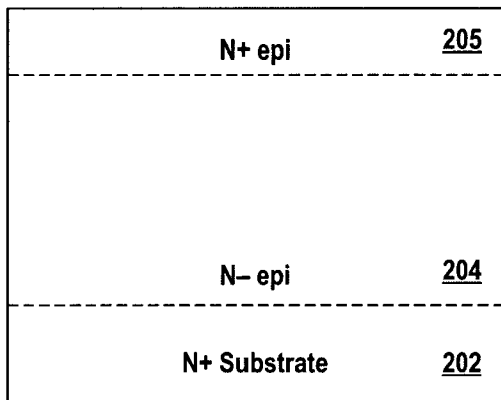


FIG. 2A

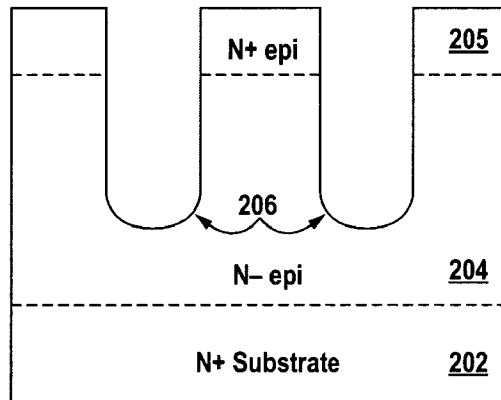


FIG. 2B

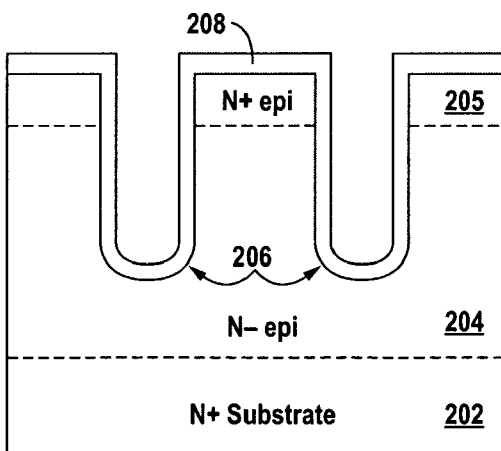


FIG. 2C

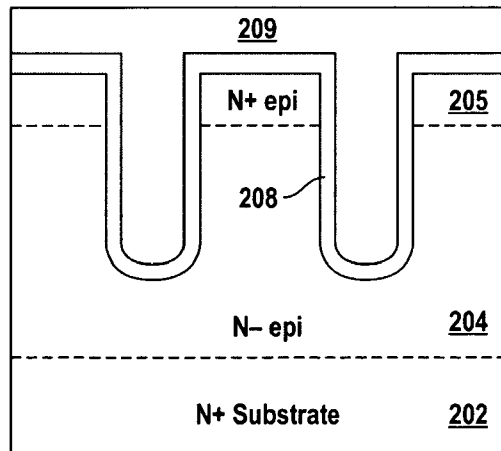


FIG. 2D

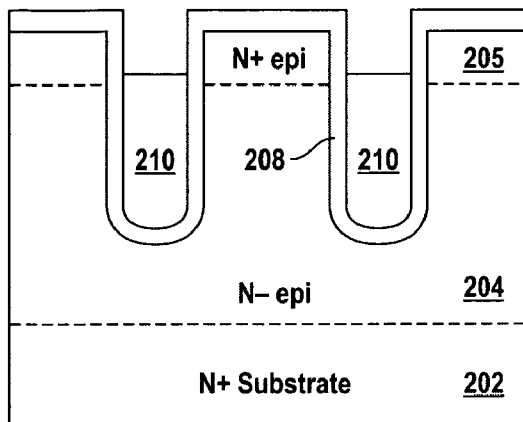


FIG. 2E

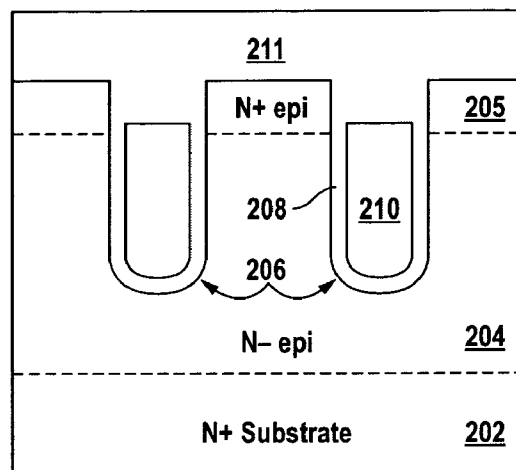


FIG. 2F

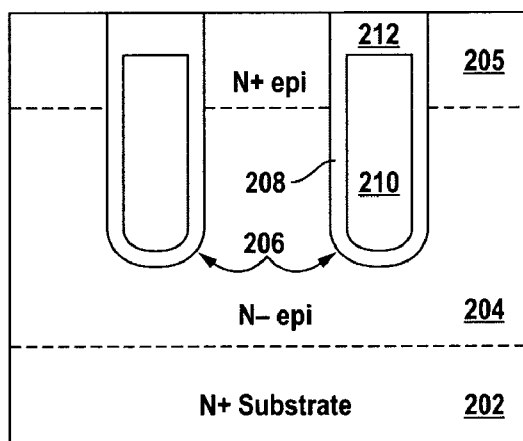


FIG. 2G

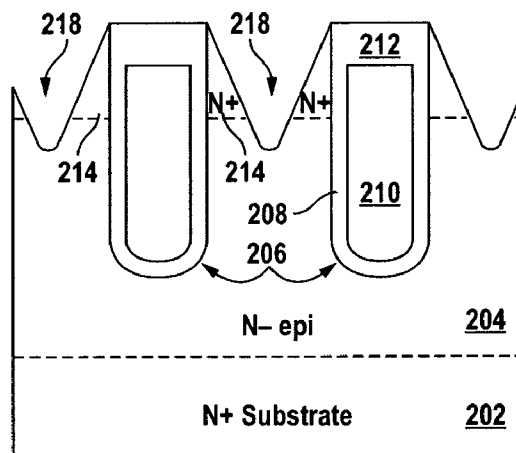


FIG. 2H

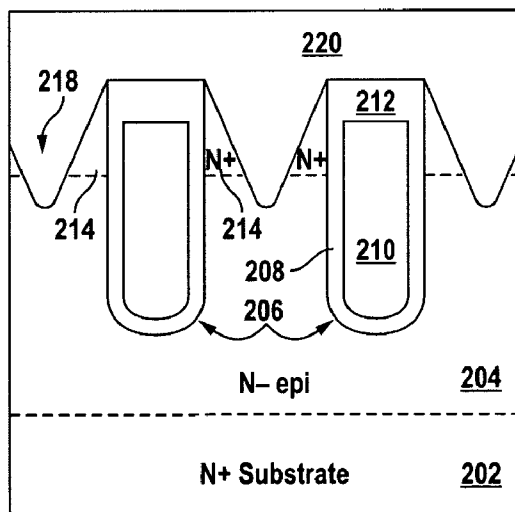


FIG. 2I

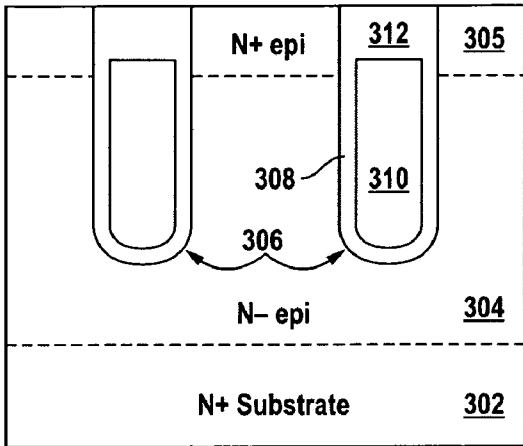


FIG. 3A

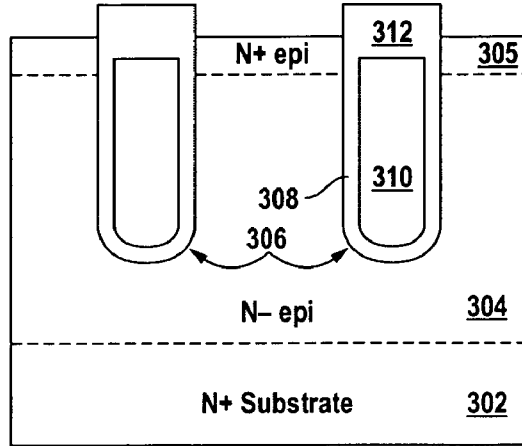


FIG. 3B

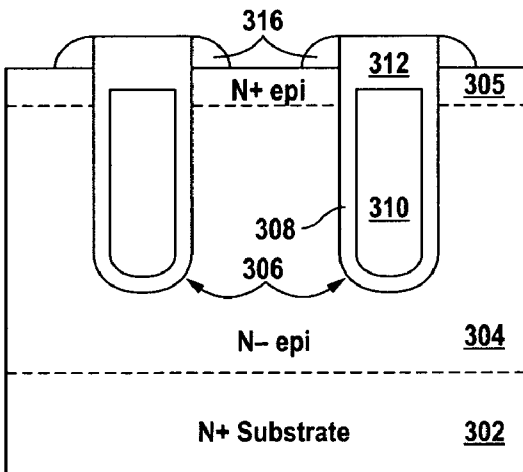


FIG. 3C

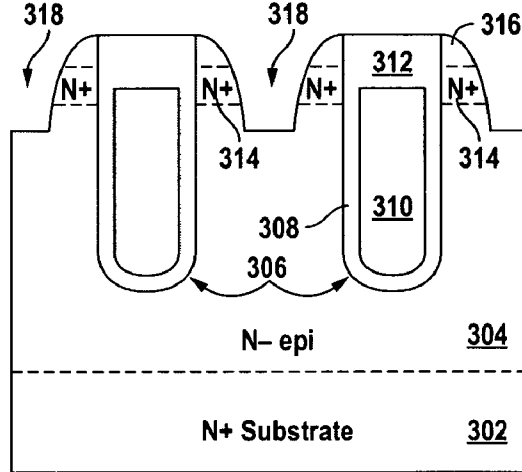


FIG. 3D

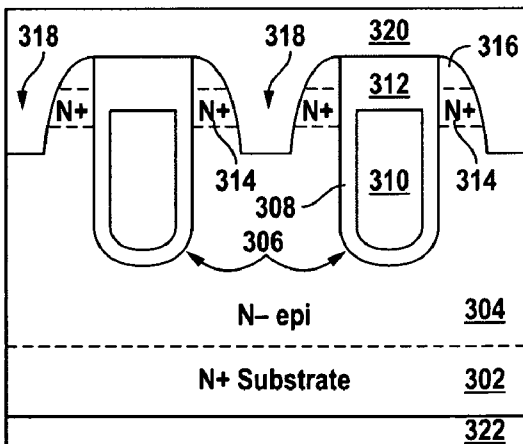


FIG. 3E

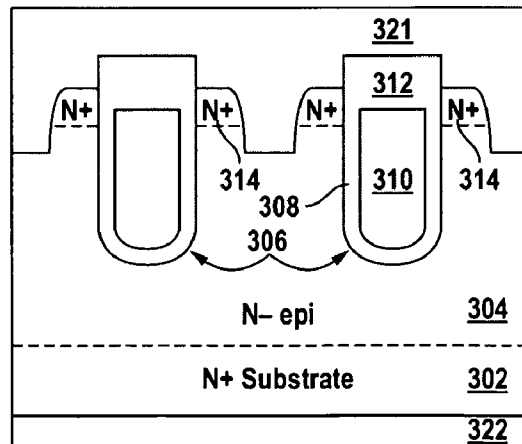


FIG. 3EE

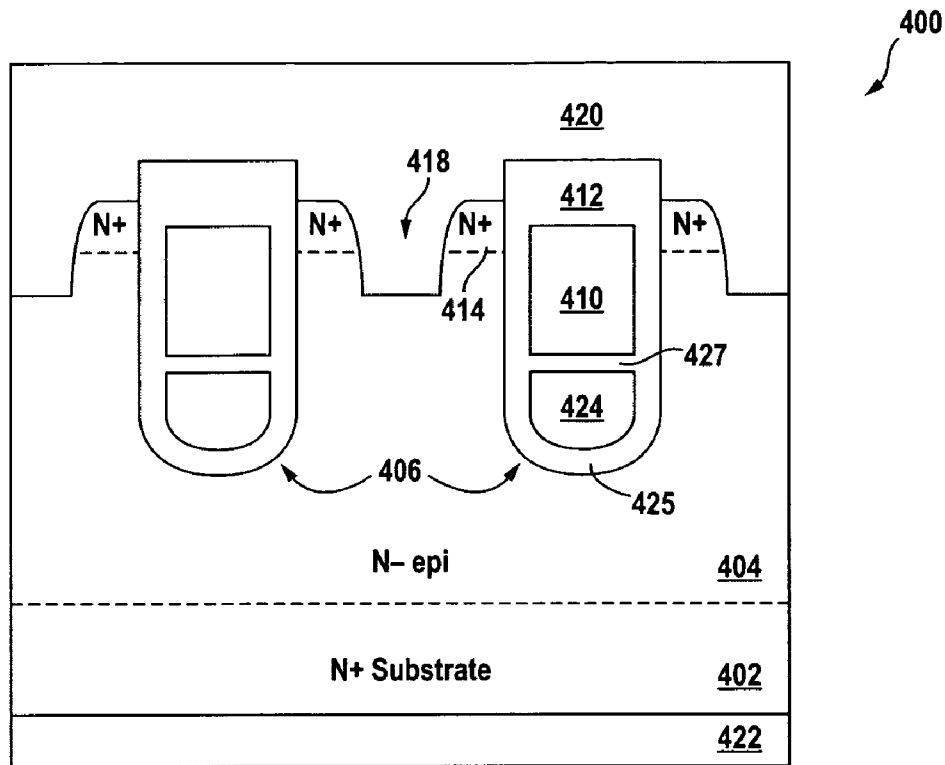


FIG. 4

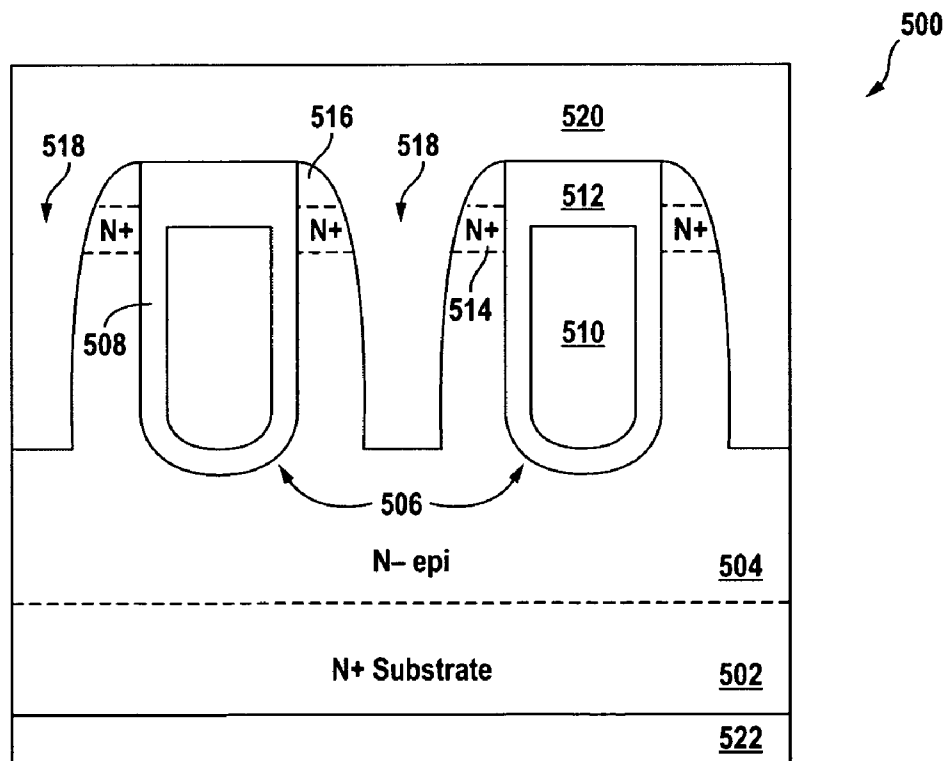


FIG. 5

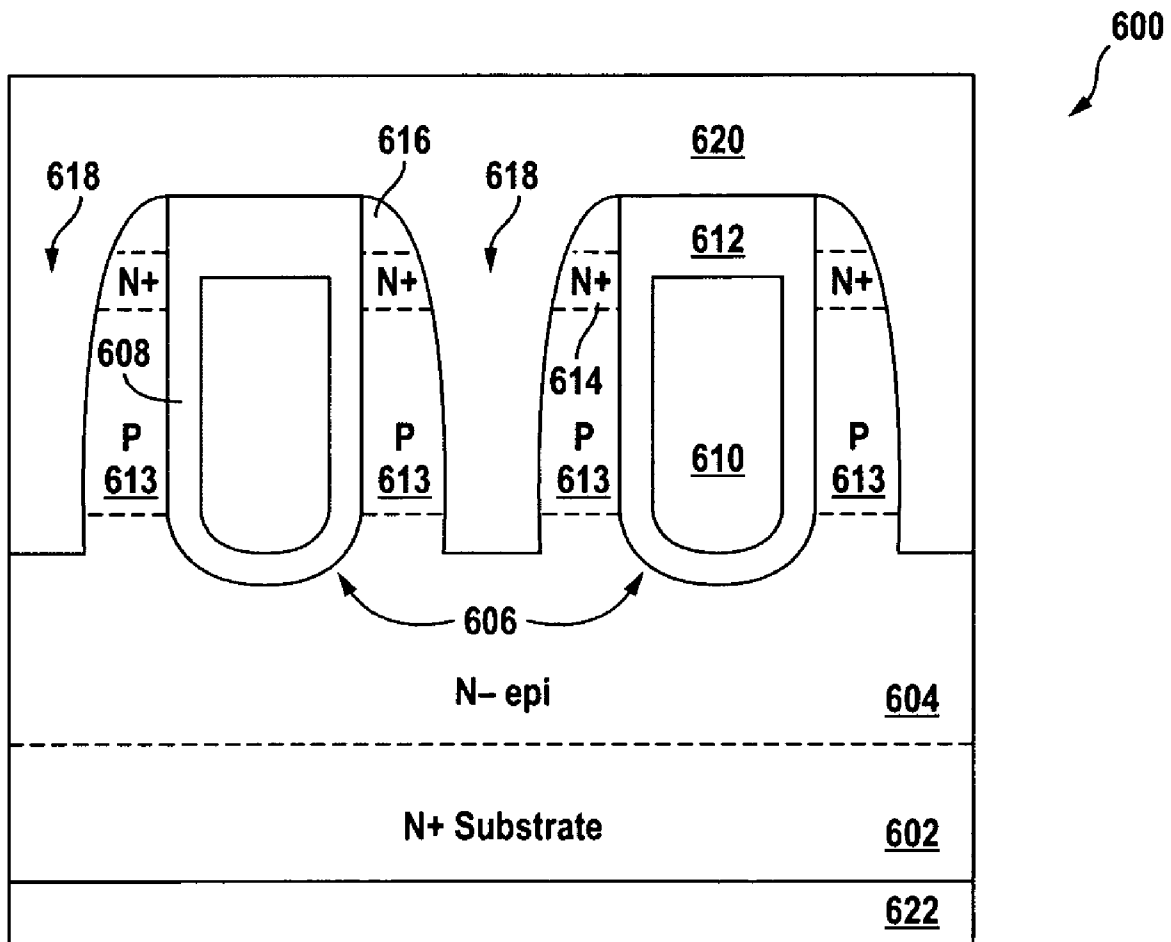


FIG. 6

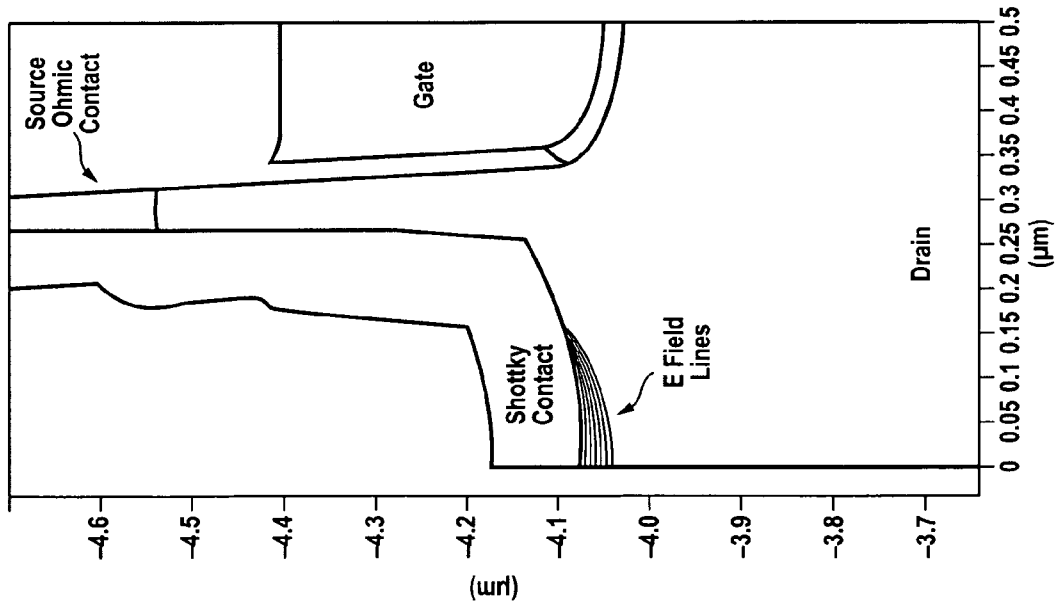
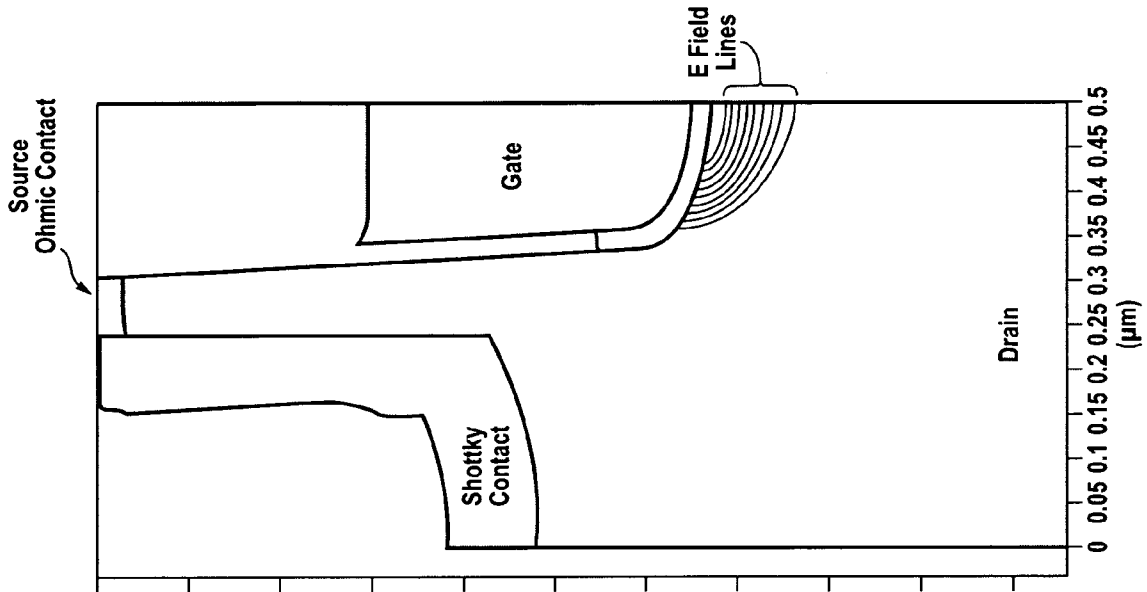


FIG. 7A

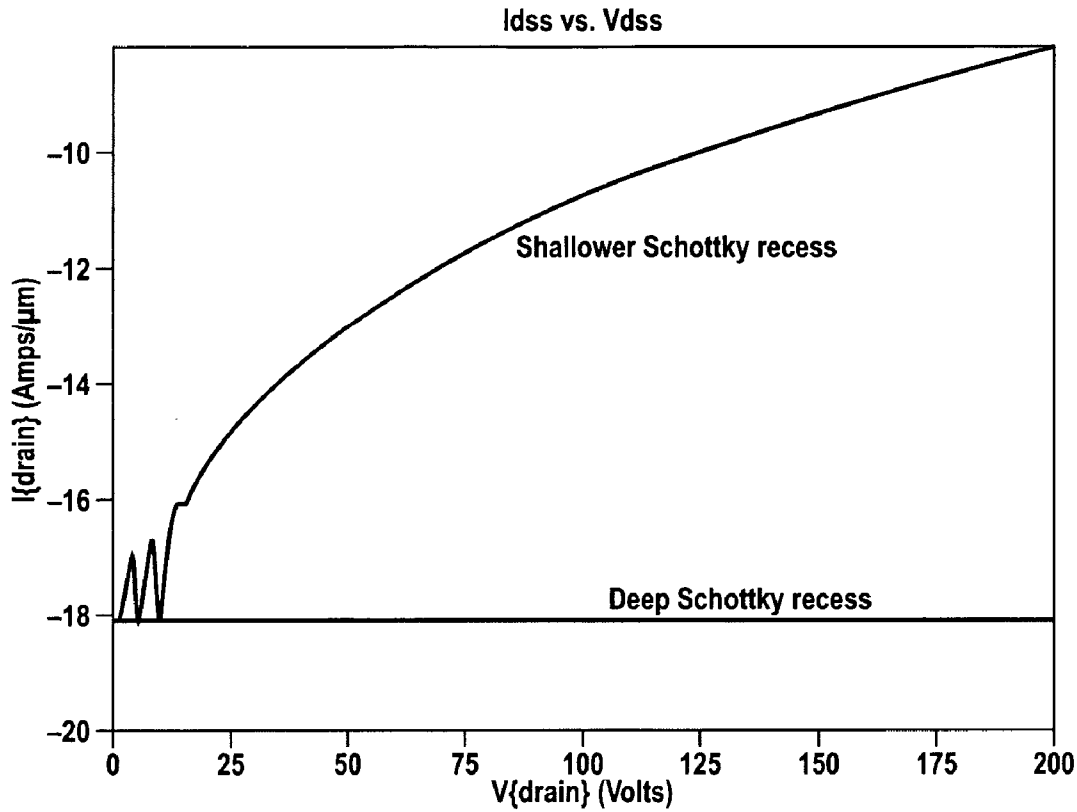


FIG. 7B

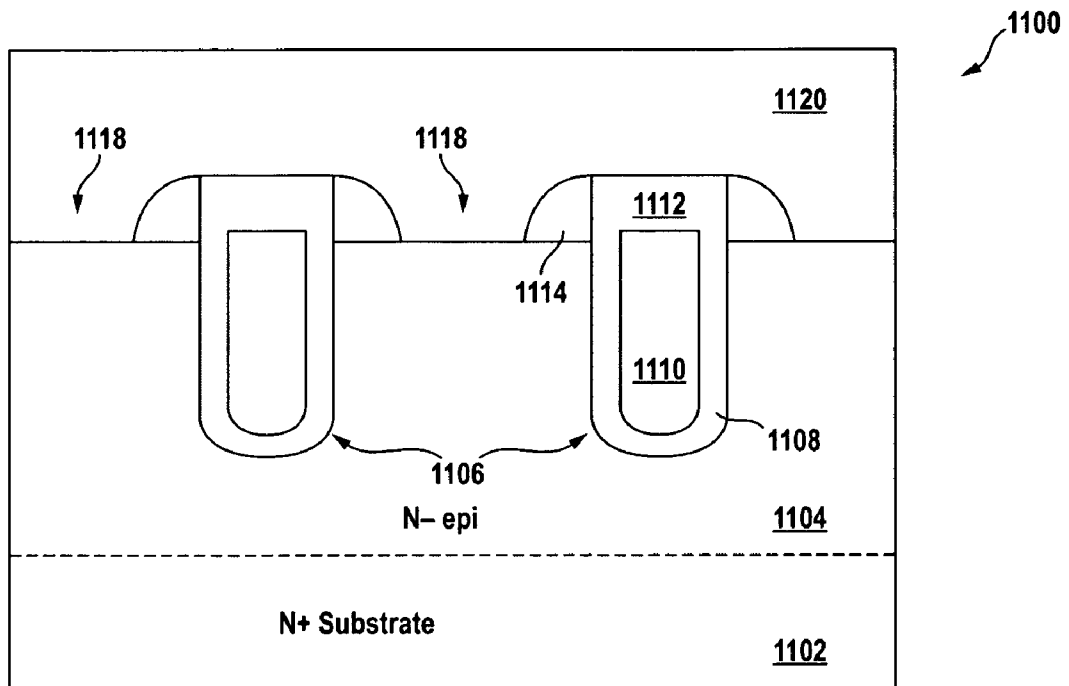


FIG. 8

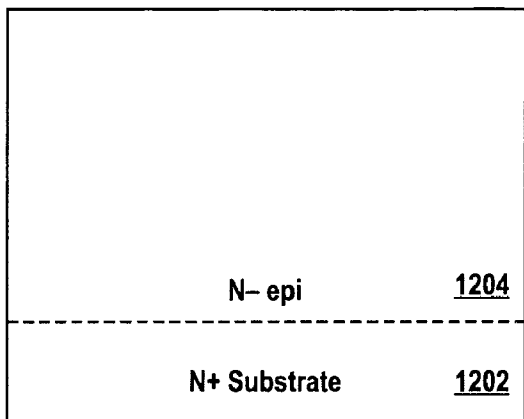


FIG. 9A

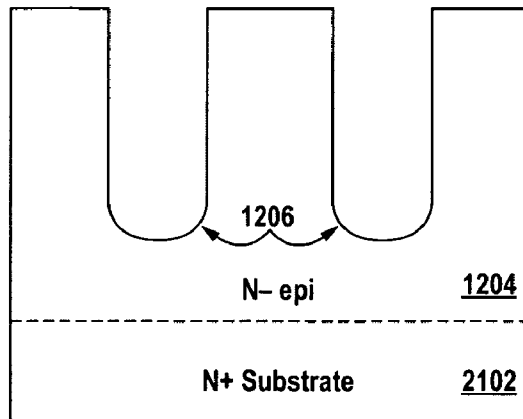


FIG. 9B

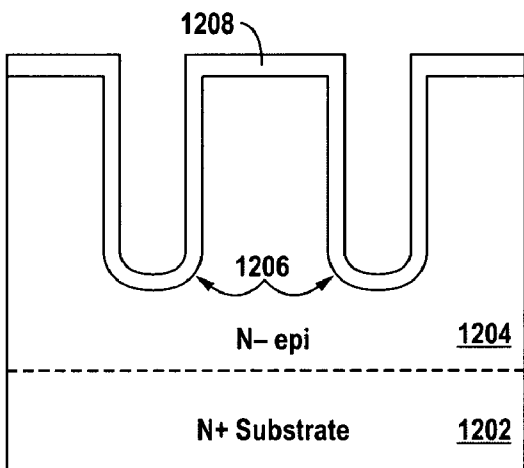


FIG. 9C

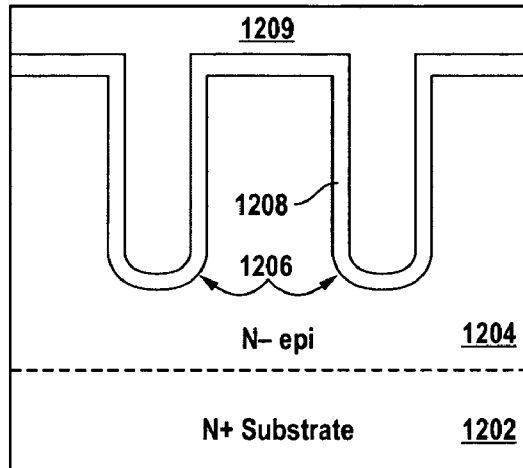


FIG. 9D

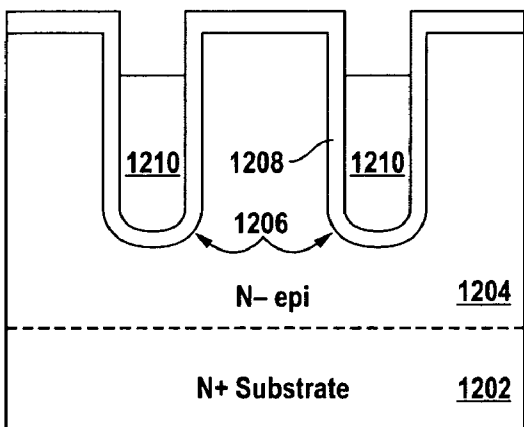


FIG. 9E

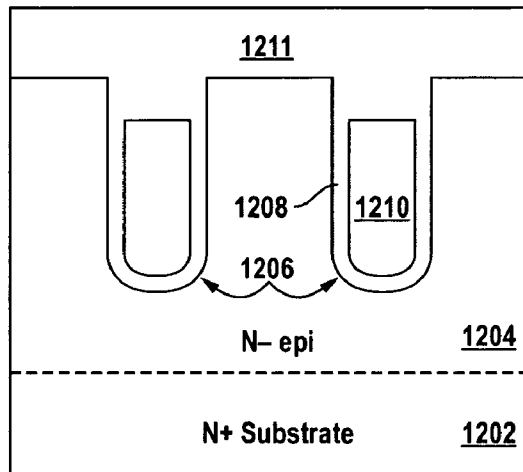


FIG. 9F

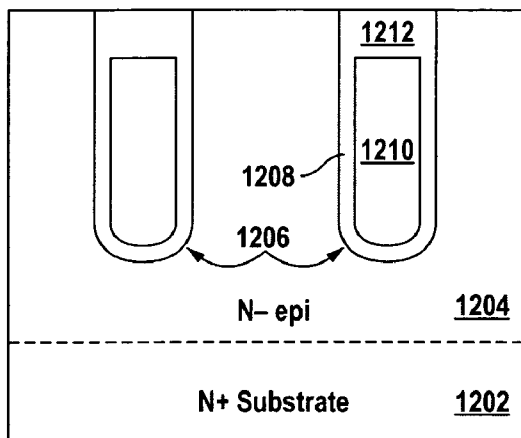


FIG. 9G

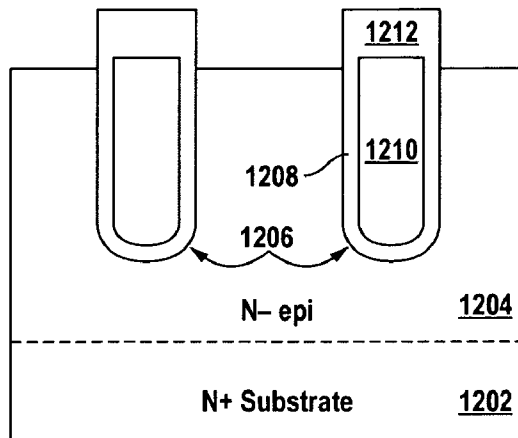


FIG. 9H

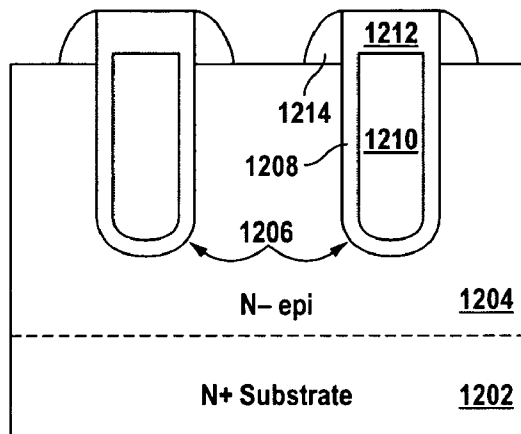


FIG. 9I-1

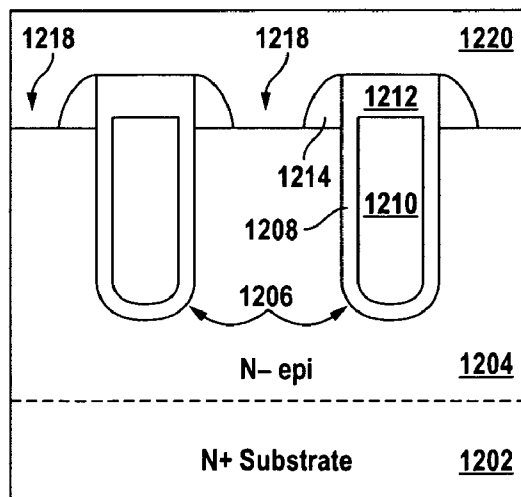


FIG. 9J-1

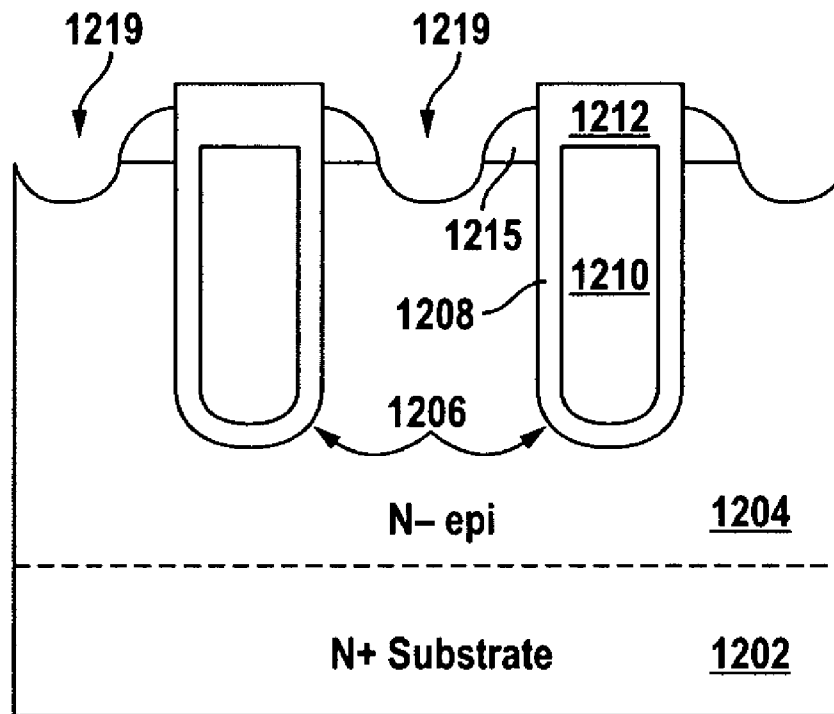


FIG. 9I-2

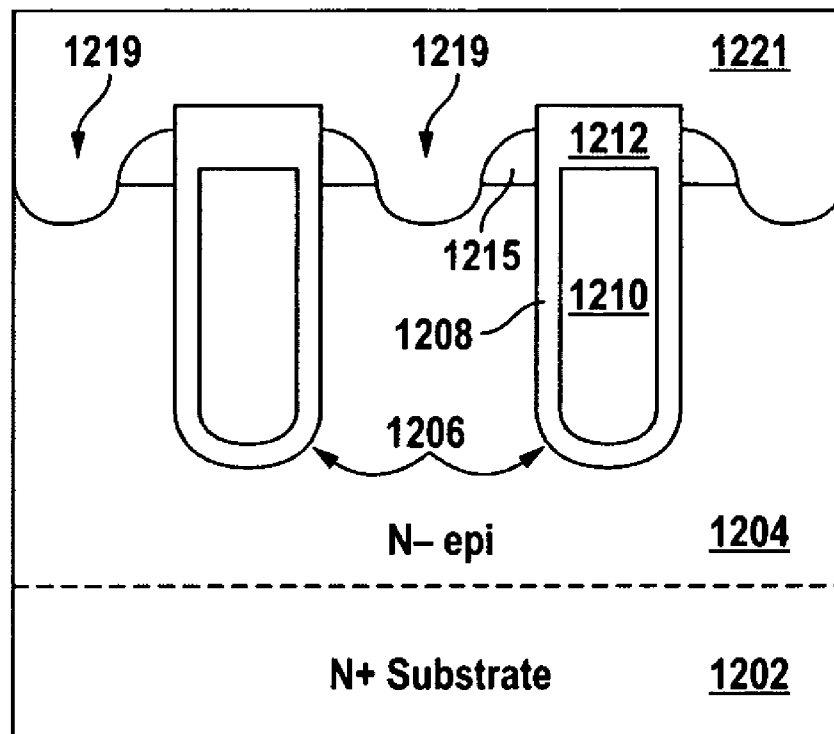


FIG. 9J-2

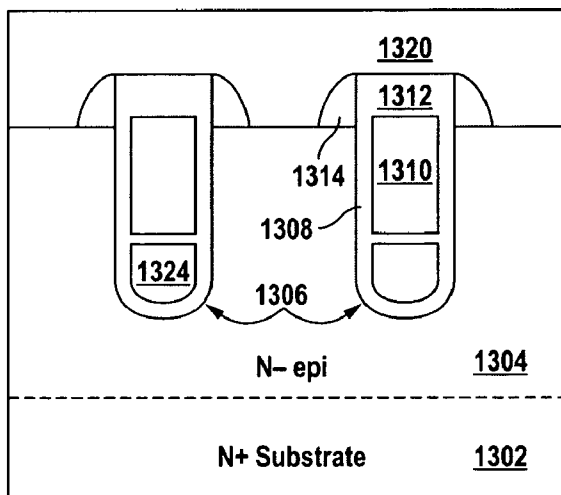


FIG. 10

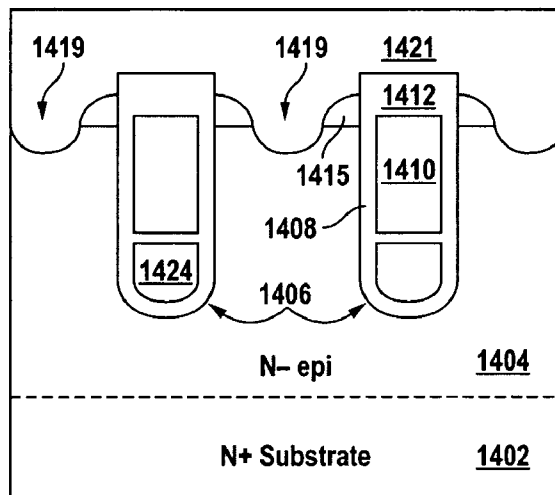


FIG. 11

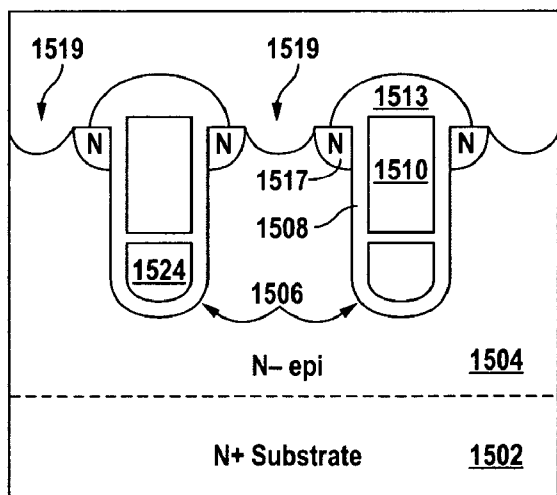


FIG. 12

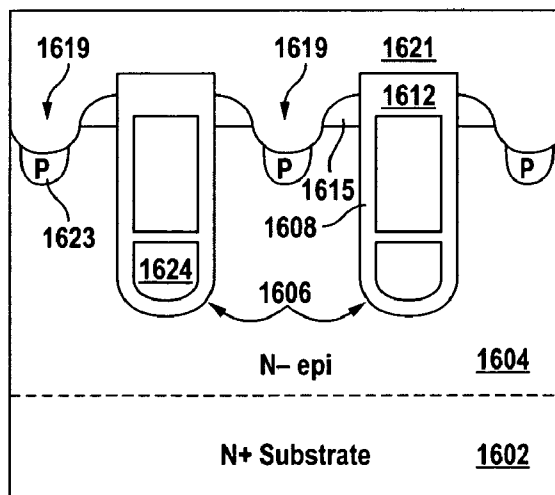


FIG. 13

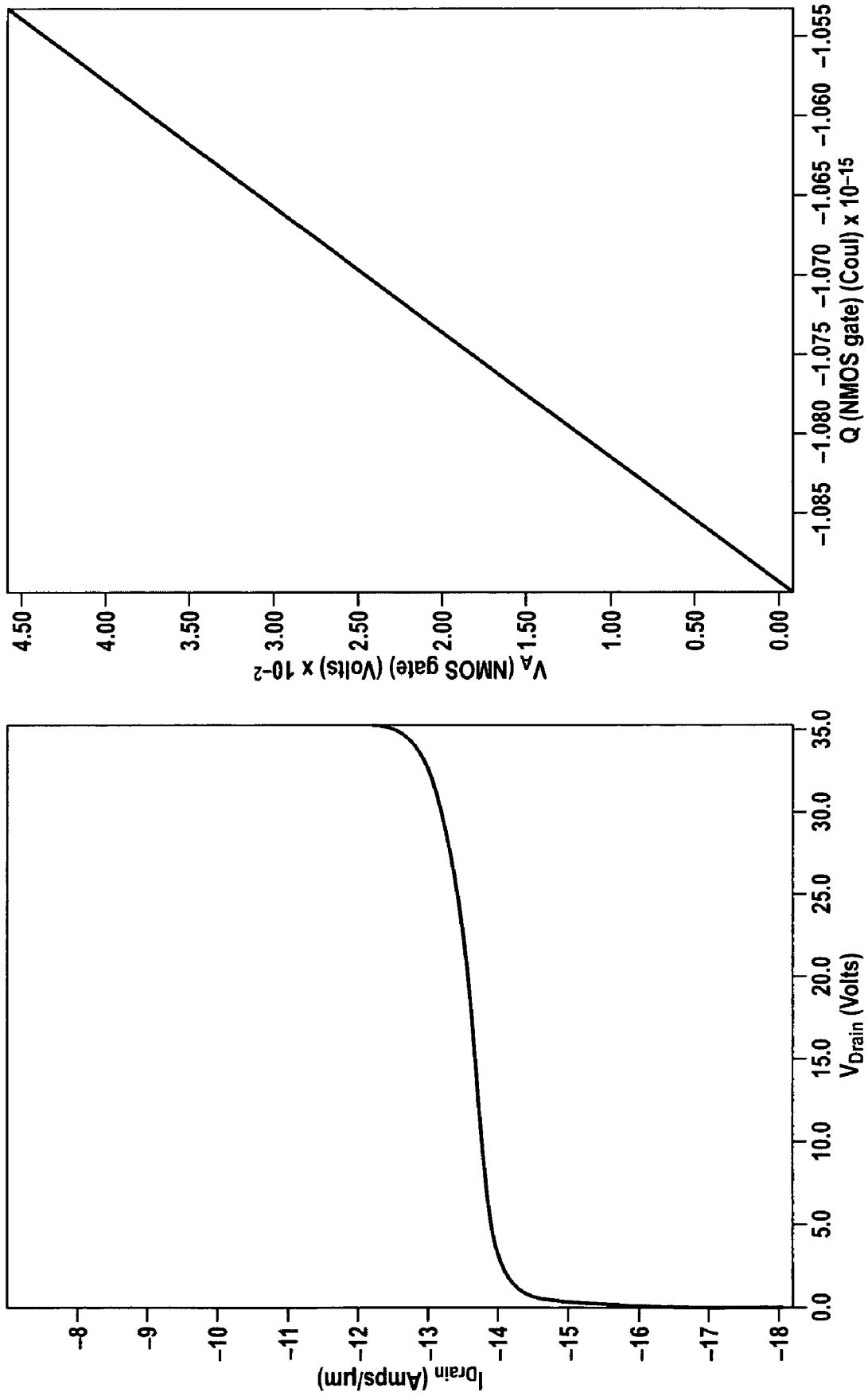


FIG. 14

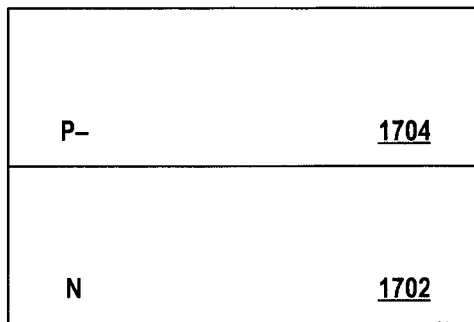


FIG. 15A

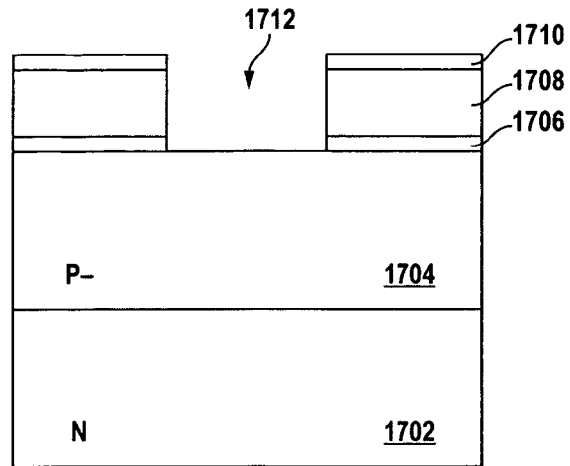


FIG. 15B

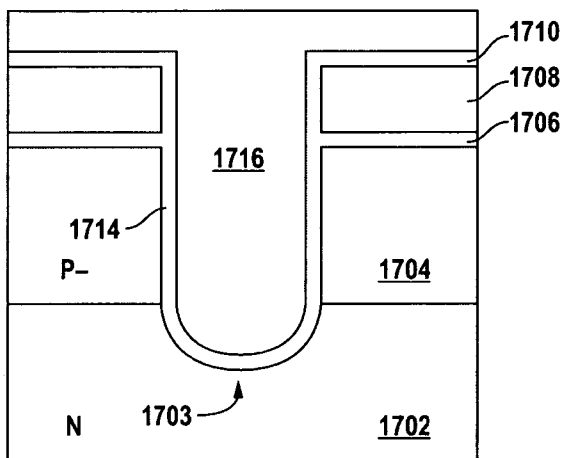


FIG. 15C

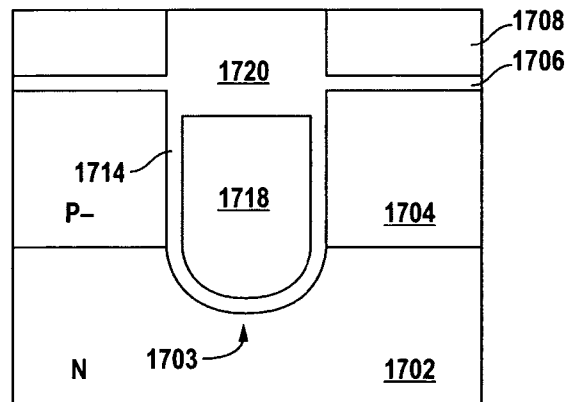


FIG. 15D

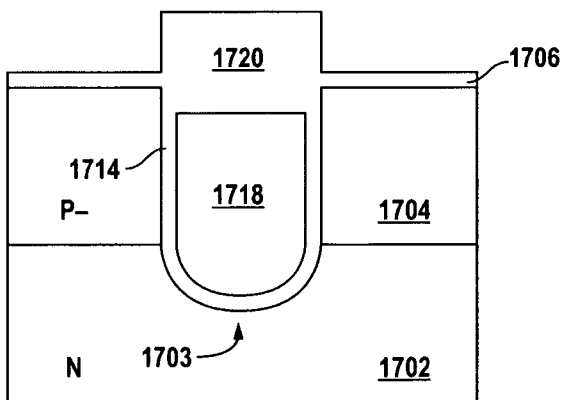


FIG. 15E

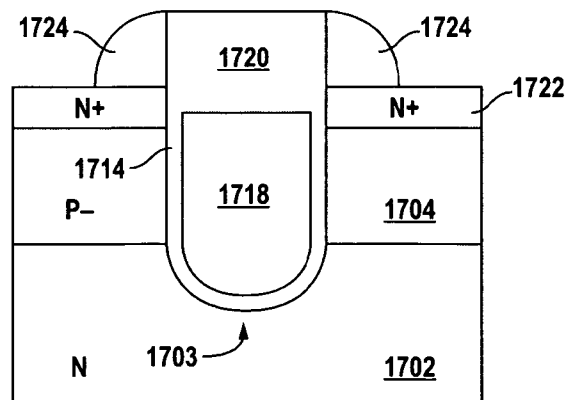


FIG. 15F

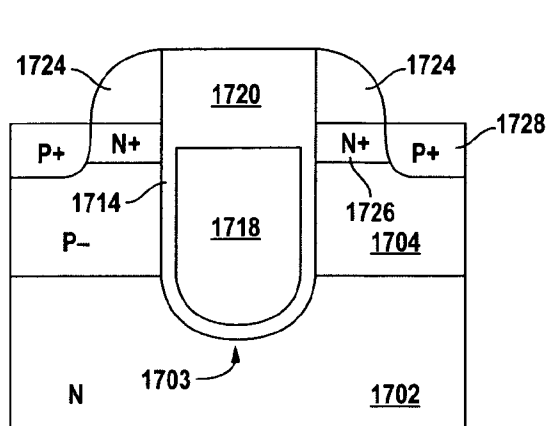


FIG. 15G

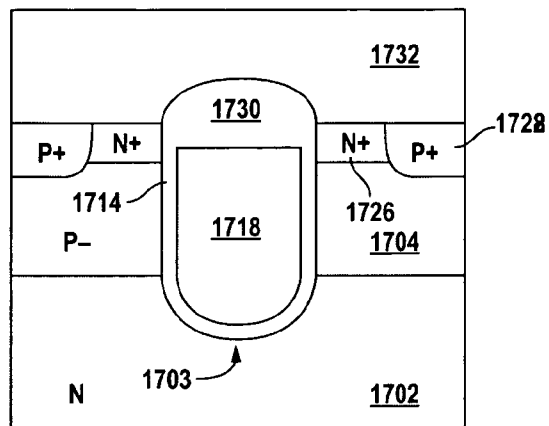


FIG. 15H

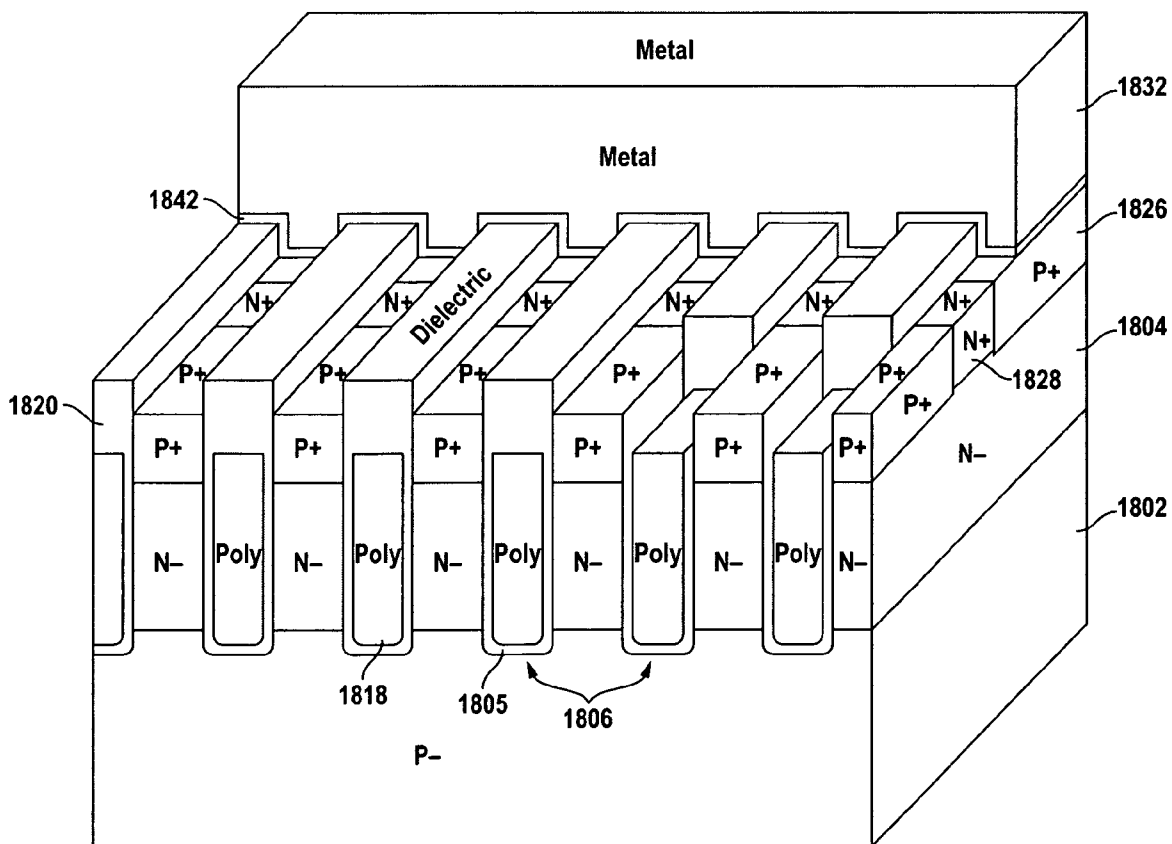


FIG. 16

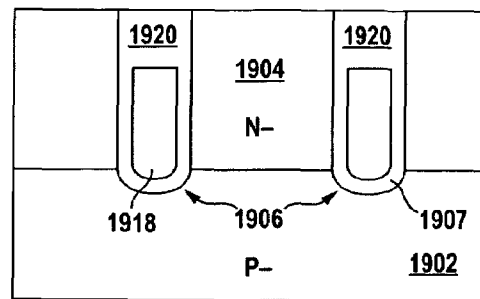


FIG. 17A

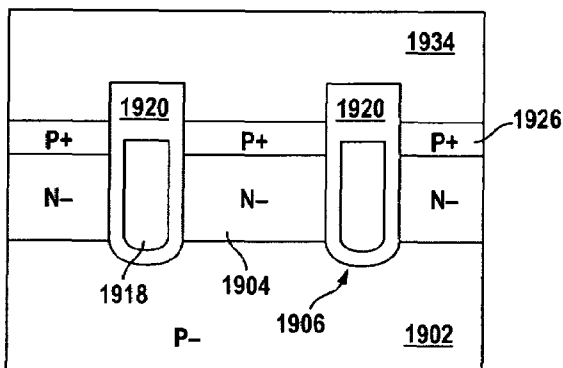


FIG. 17B-1

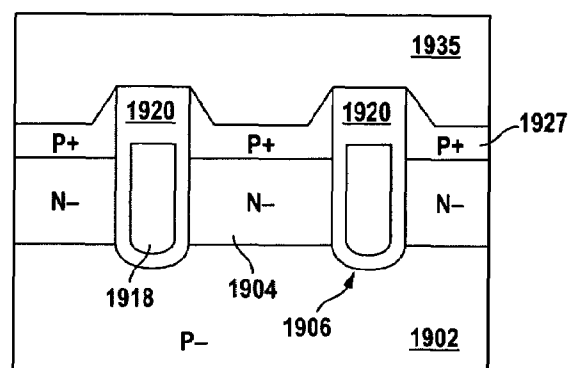


FIG. 17B-2

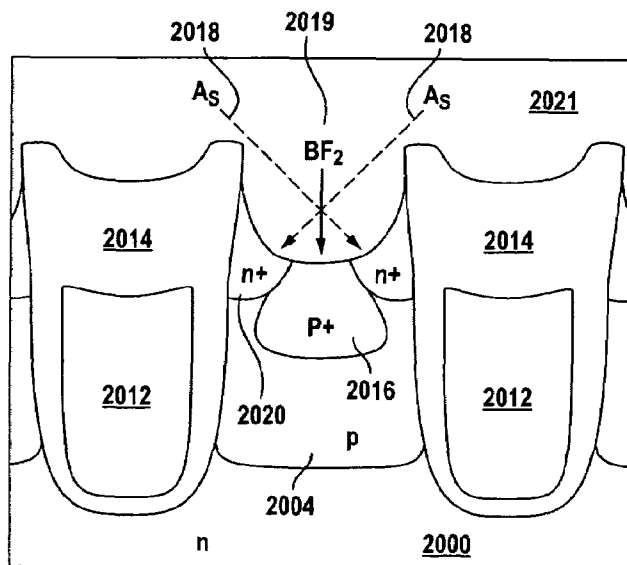


FIG. 18

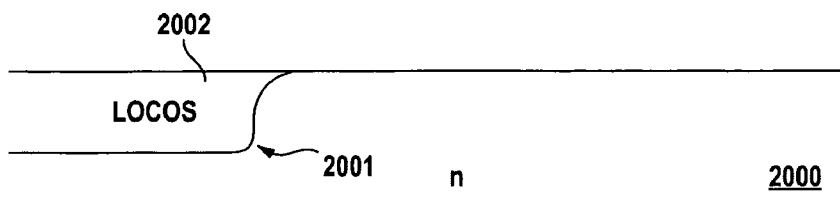


FIG. 18A

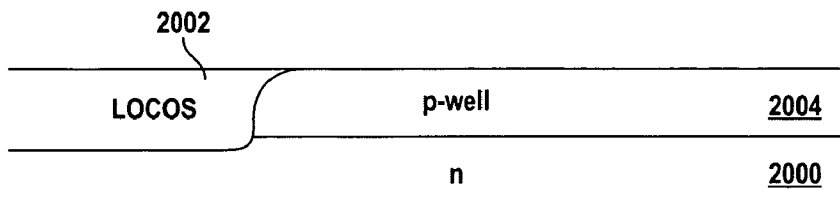


FIG. 18B

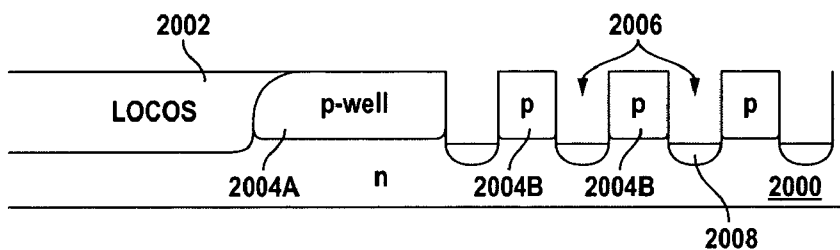


FIG. 18C

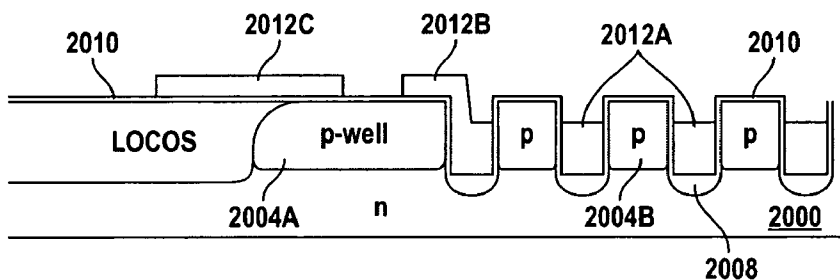


FIG. 18D

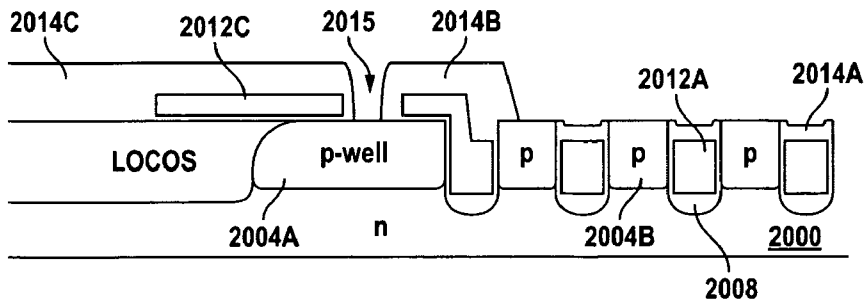


FIG. 18E

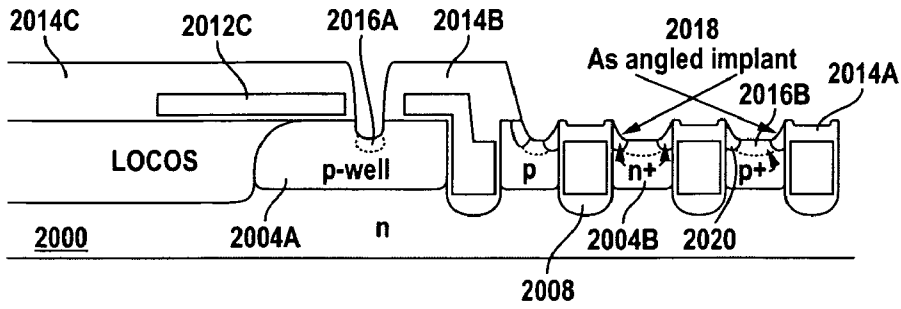


FIG. 18F

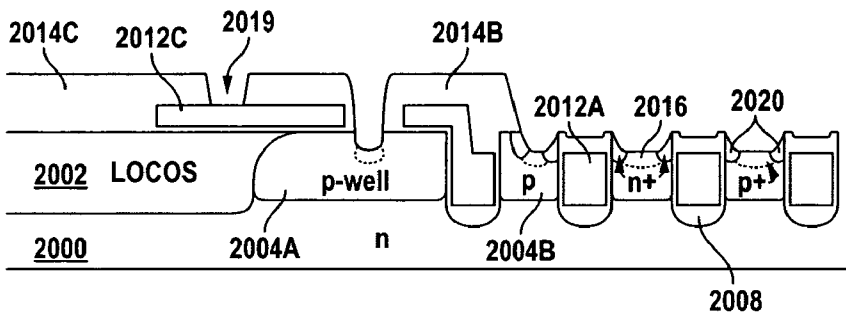


FIG. 18G

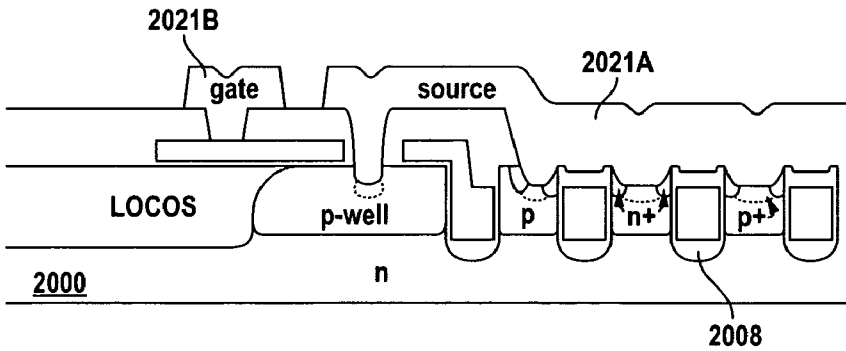


FIG. 18H

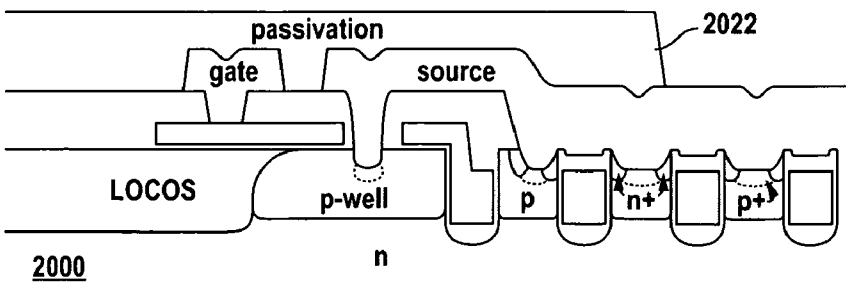


FIG. 18I

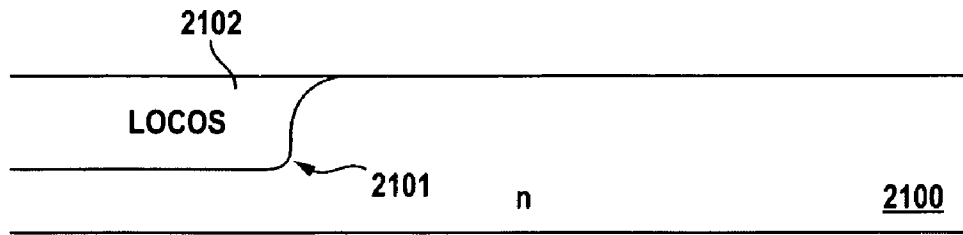


FIG. 19A

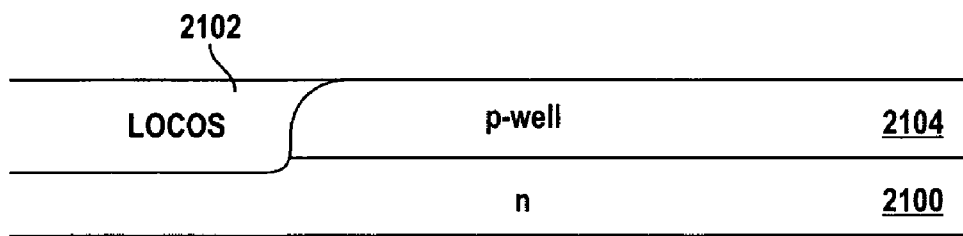


FIG. 19B

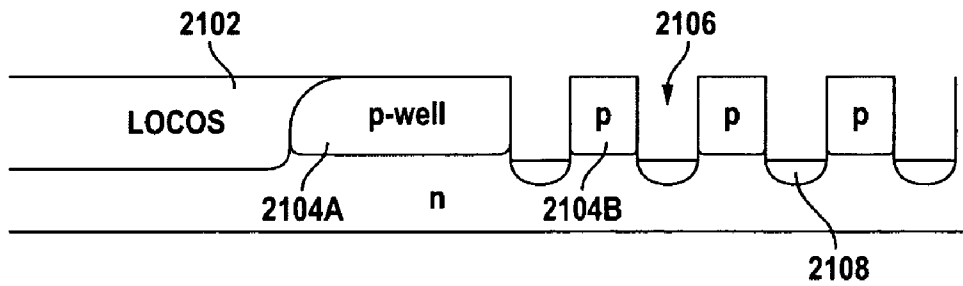


FIG. 19C

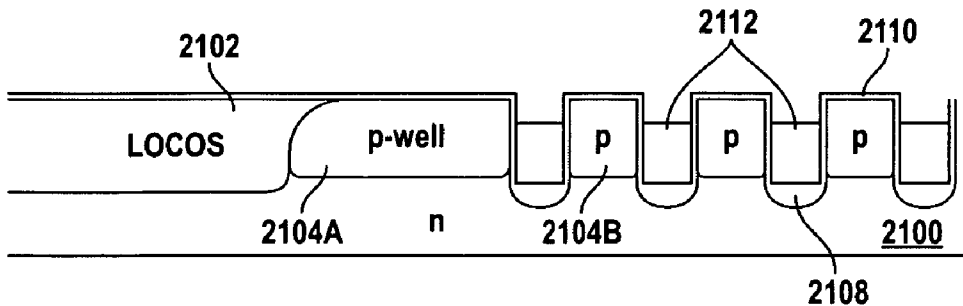


FIG. 19D

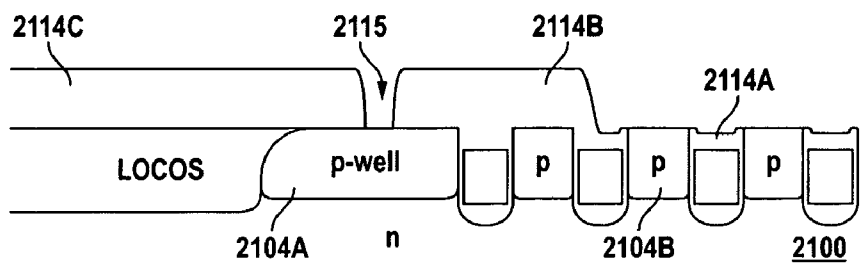


FIG. 19E

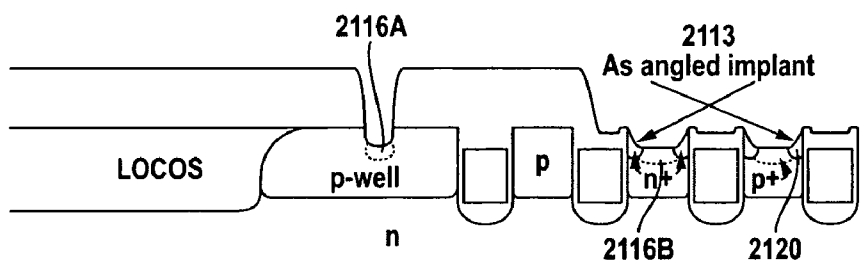


FIG. 19F

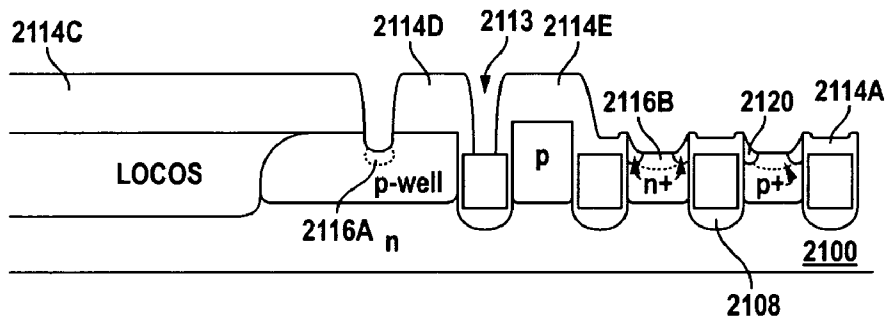


FIG. 19G

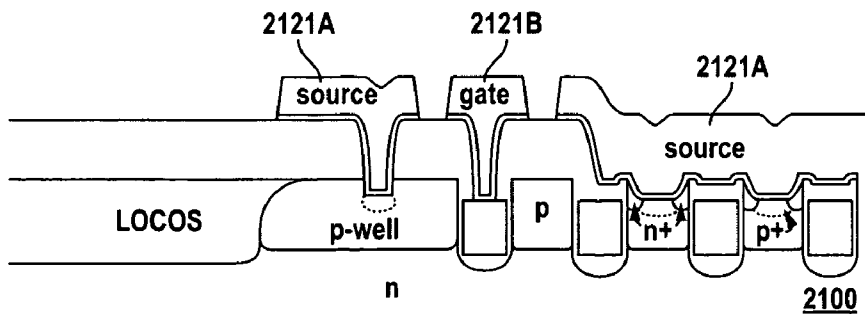


FIG. 19H

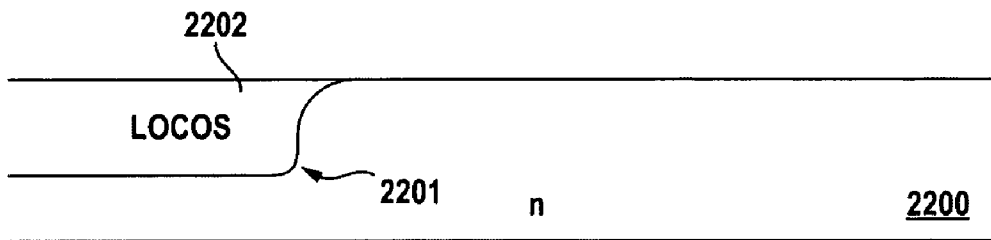


FIG. 20A

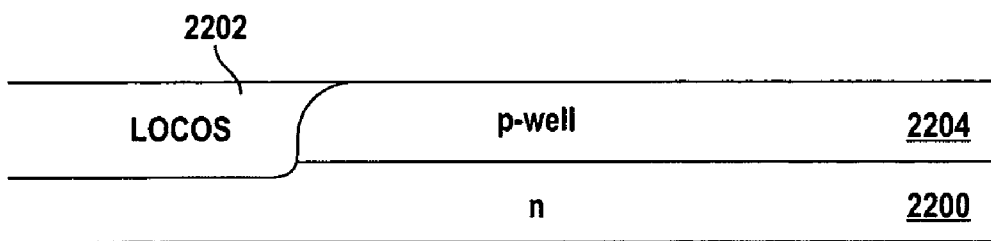


FIG. 20B

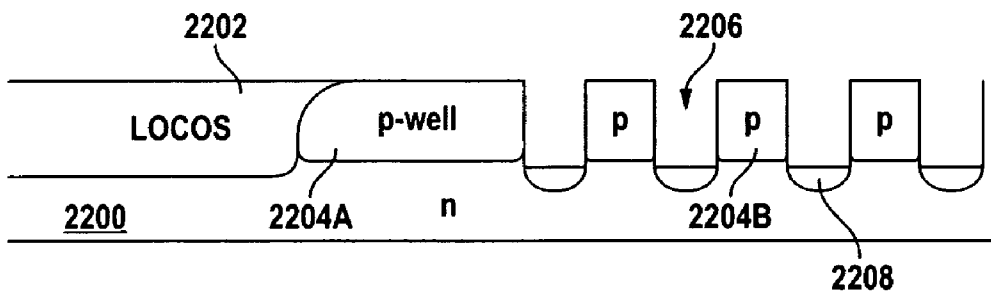


FIG. 20C

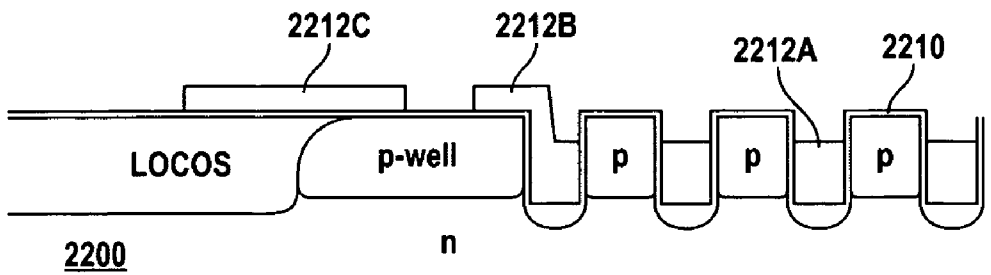


FIG. 20D

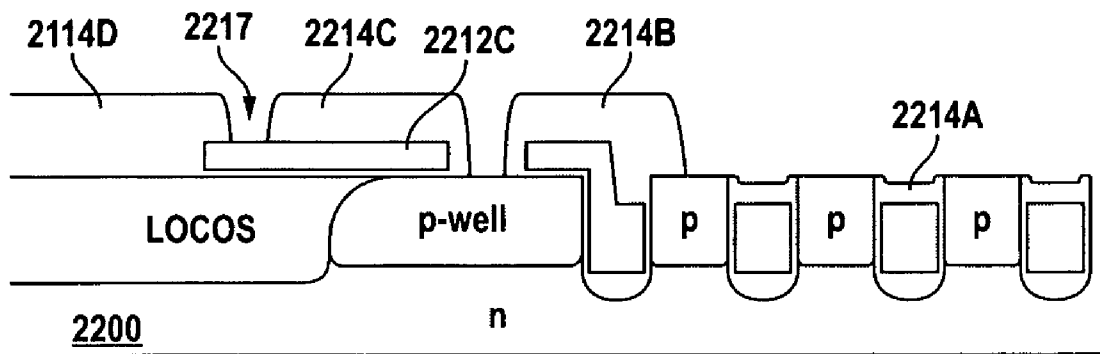


FIG. 20E

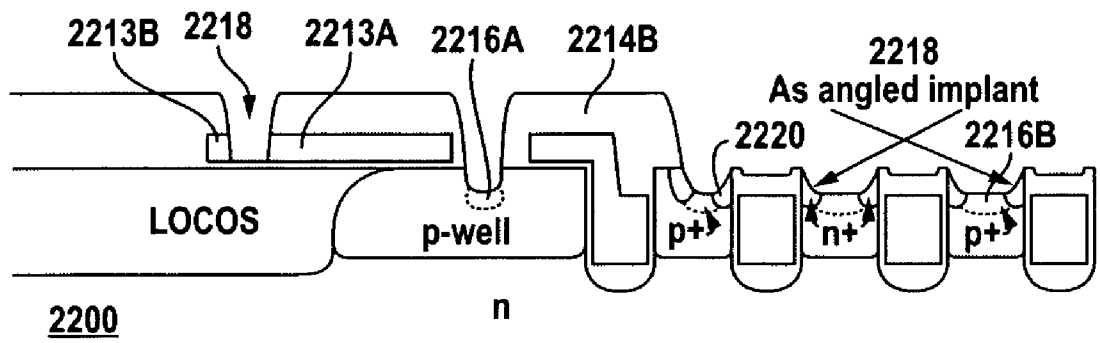


FIG. 20F

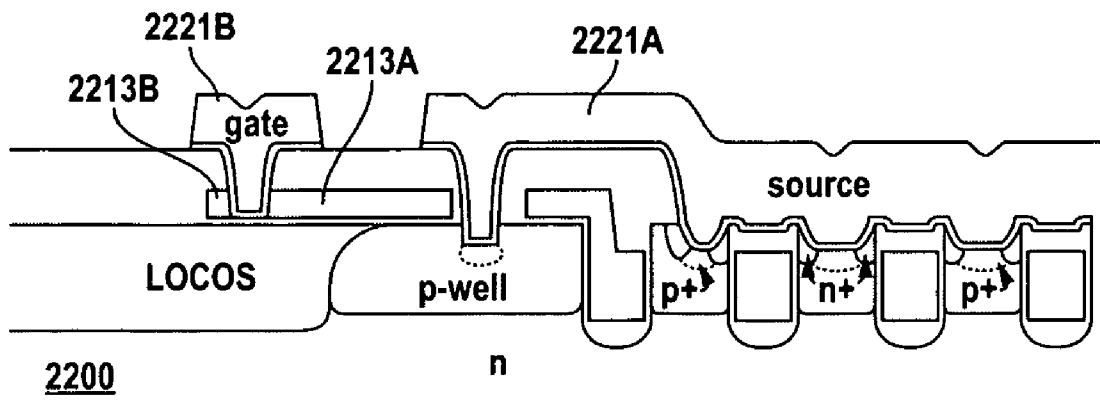


FIG. 20G

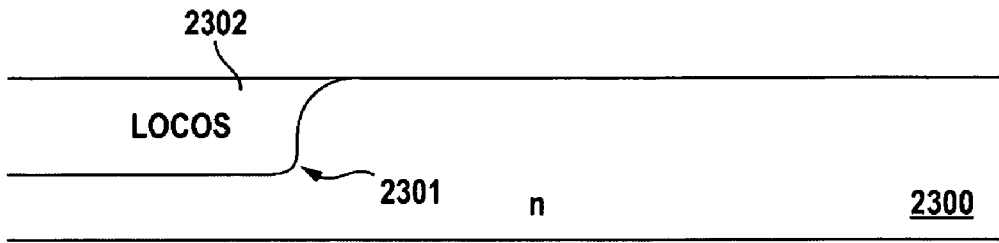


FIG. 21A

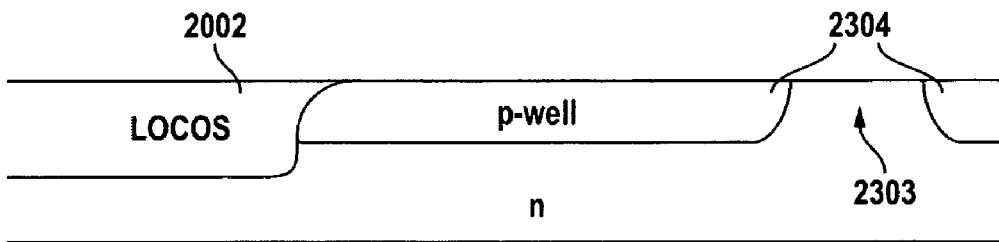


FIG. 21B

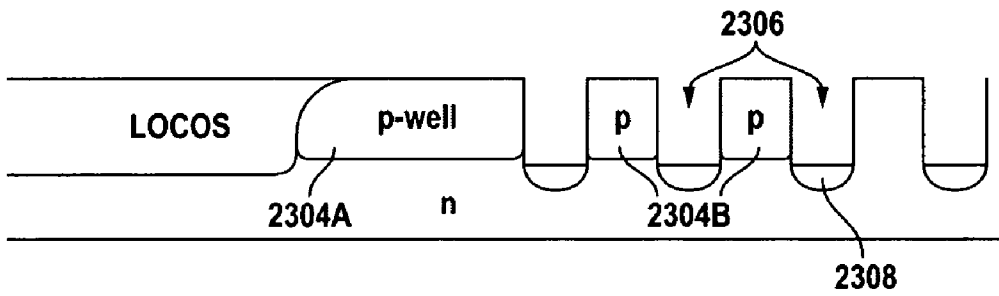


FIG. 21C

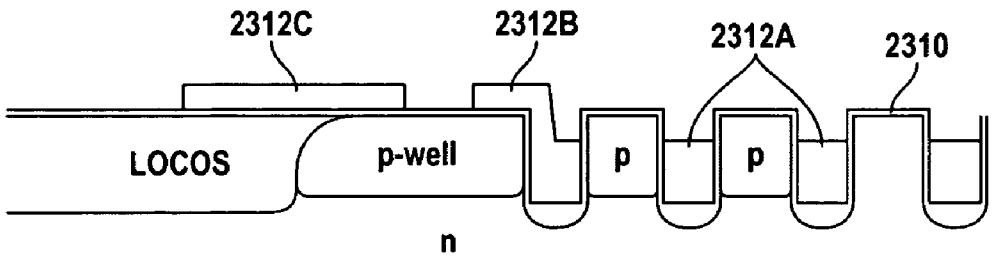


FIG. 21D

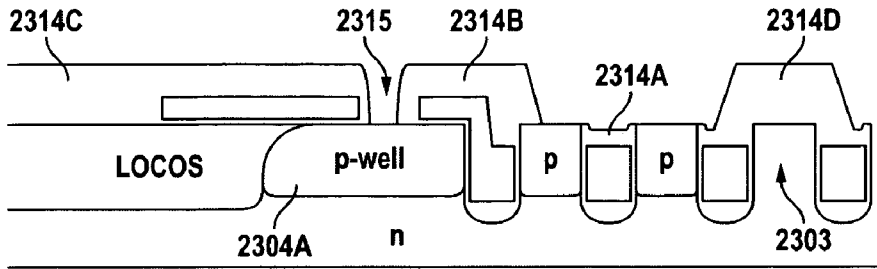


FIG. 21E

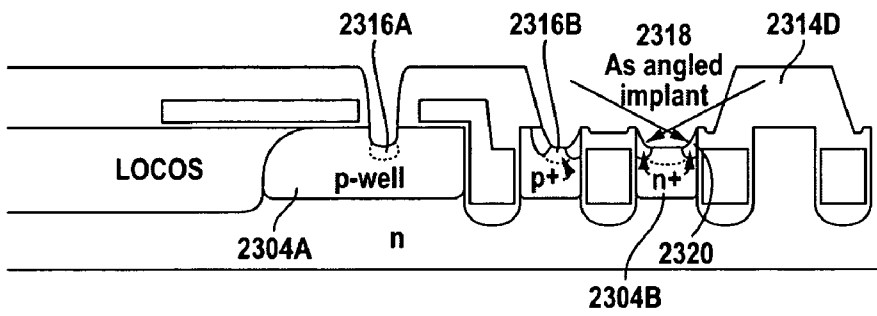


FIG. 21F

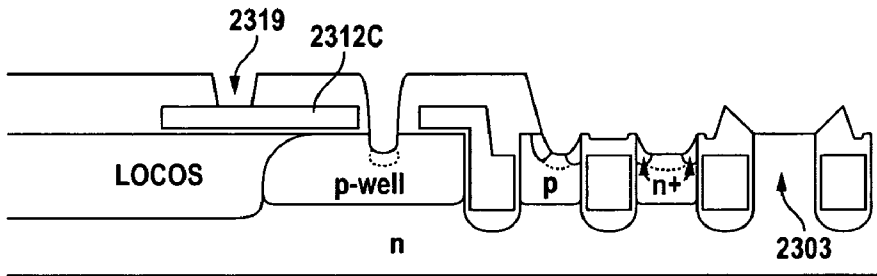


FIG. 21G

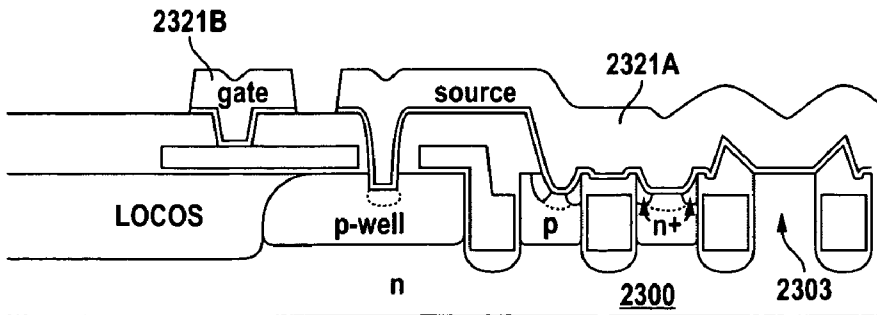


FIG. 21H

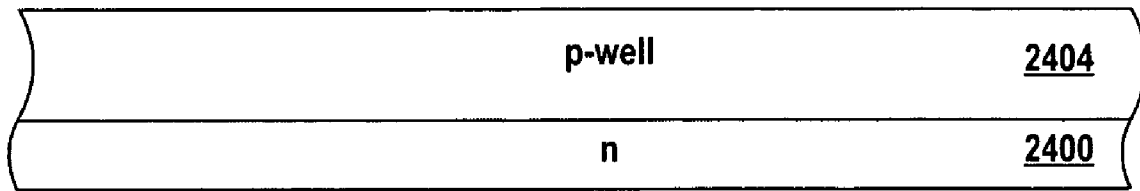


FIG. 22A

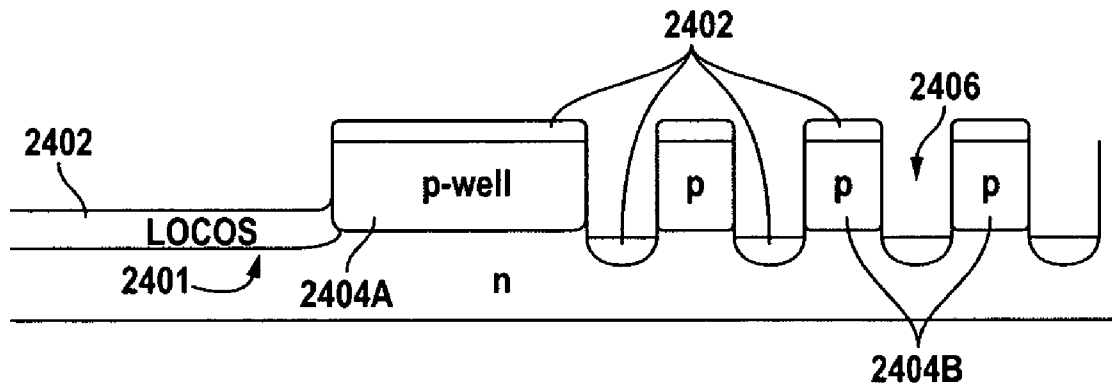


FIG. 22B

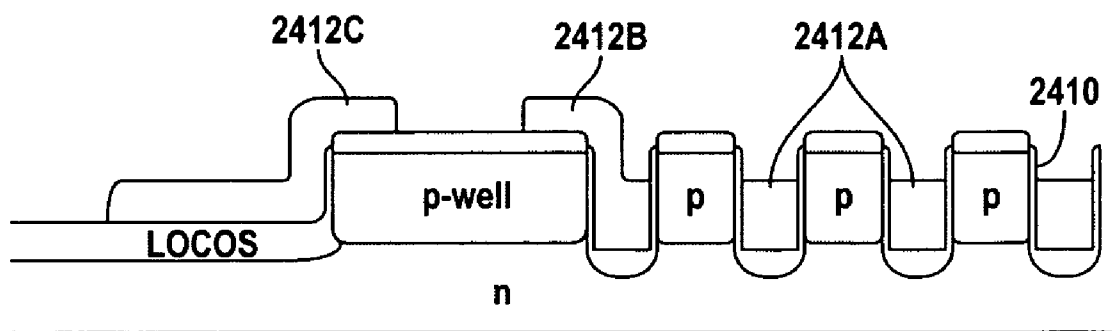


FIG. 22C

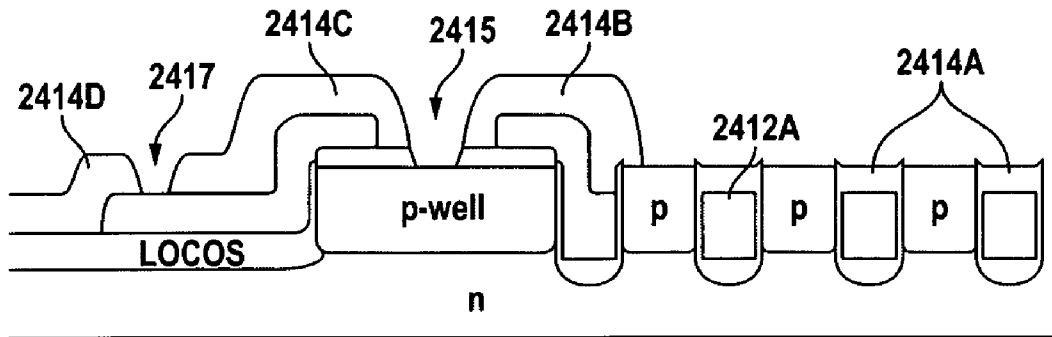


FIG. 22D

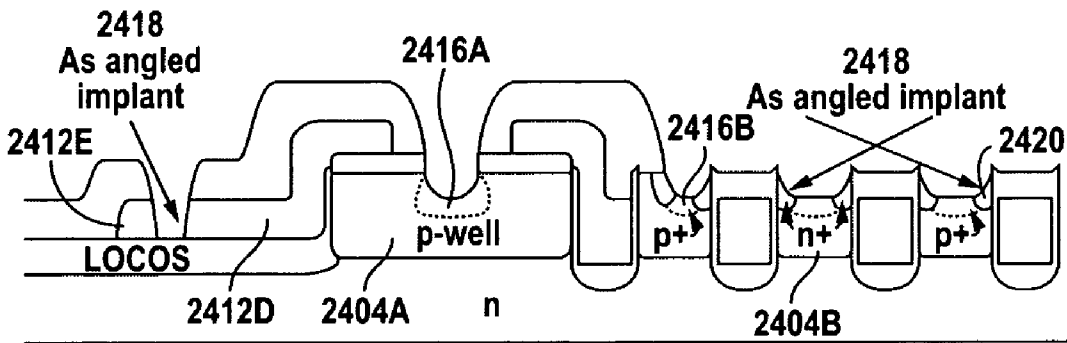


FIG. 22E

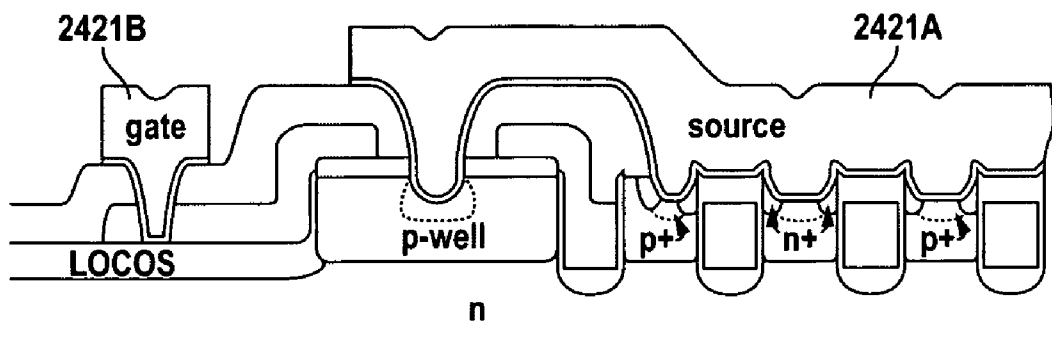


FIG. 22F

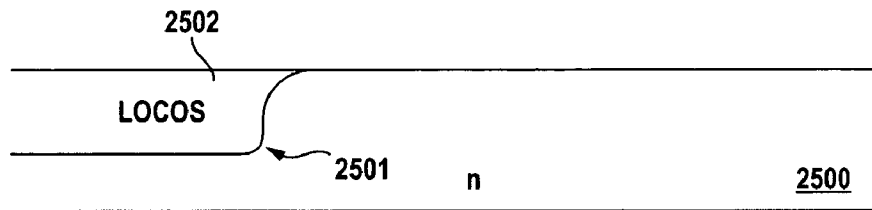


FIG. 23A

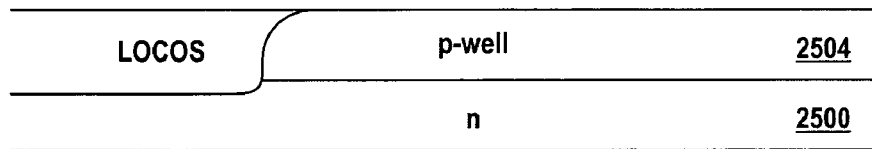


FIG. 23B

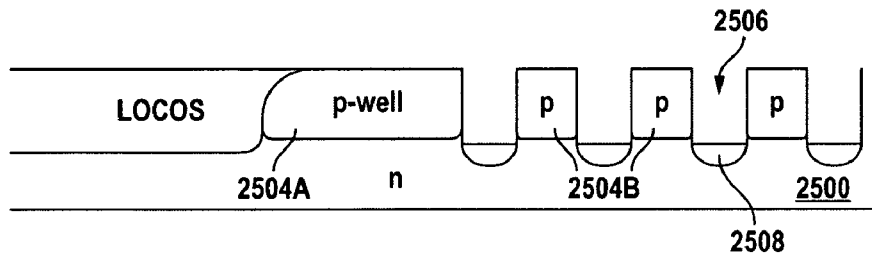


FIG. 23C

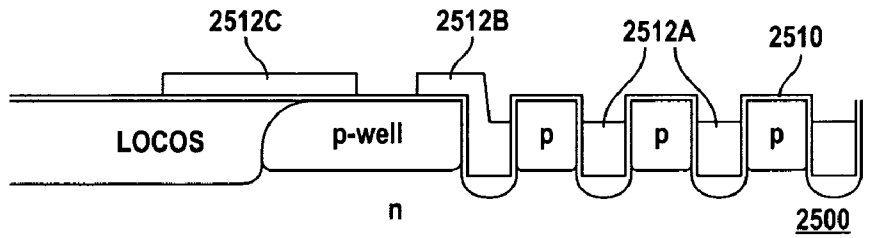


FIG. 23D

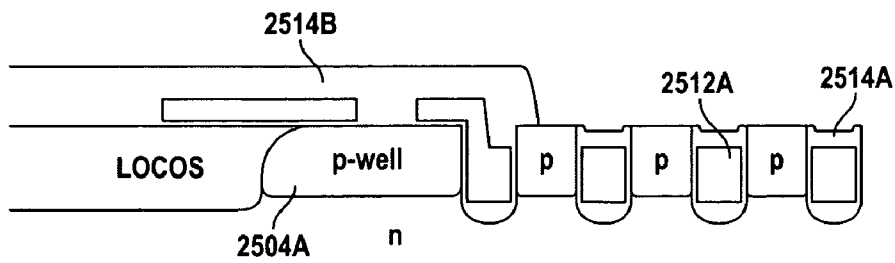


FIG. 23E

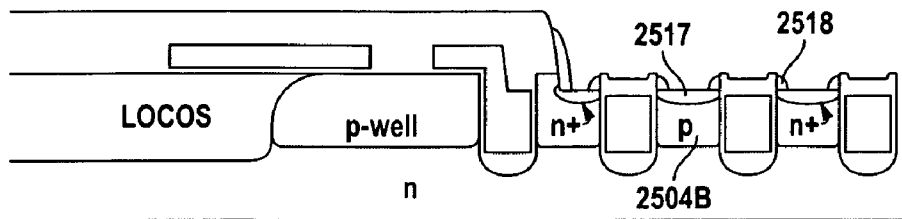


FIG. 23F

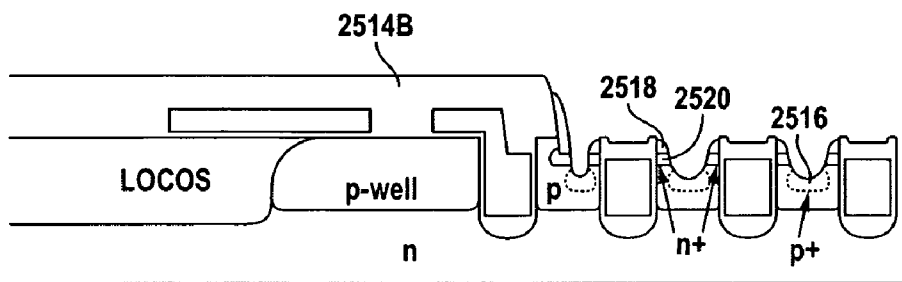


FIG. 23G

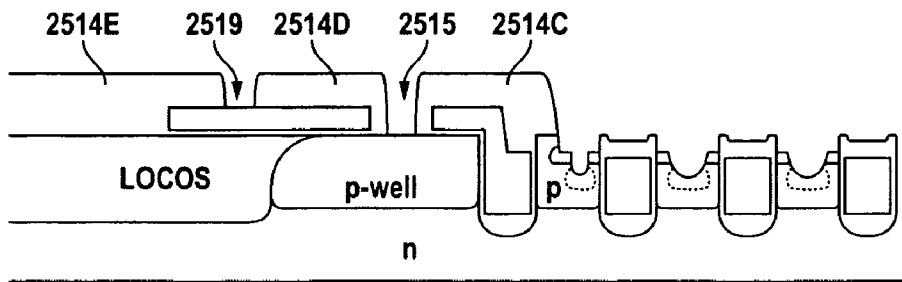


FIG. 23H

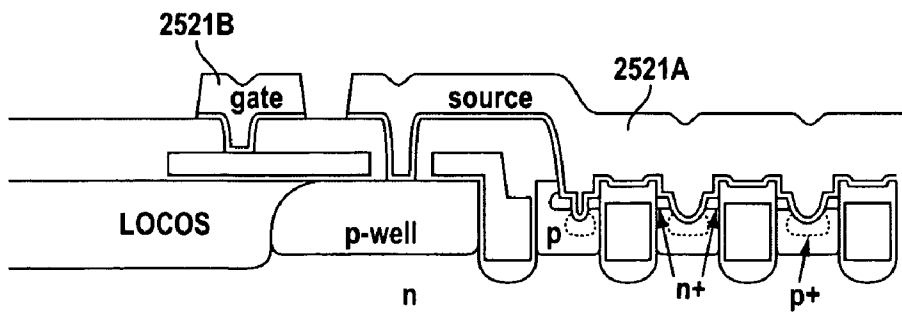


FIG. 23I

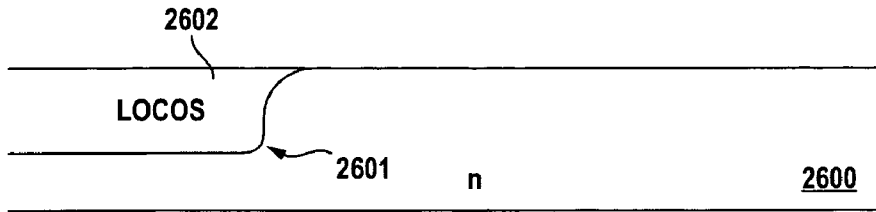


FIG. 24A

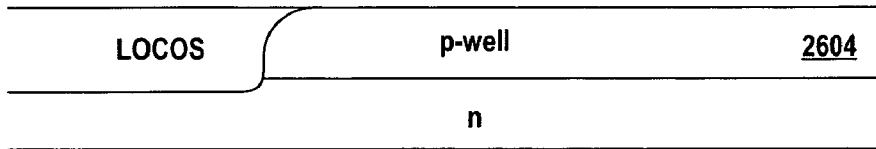


FIG. 24B

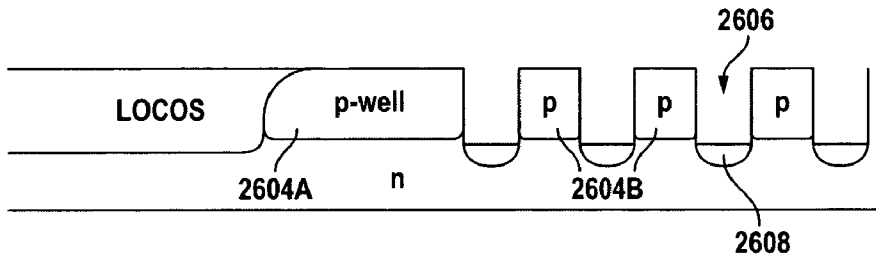


FIG. 24C

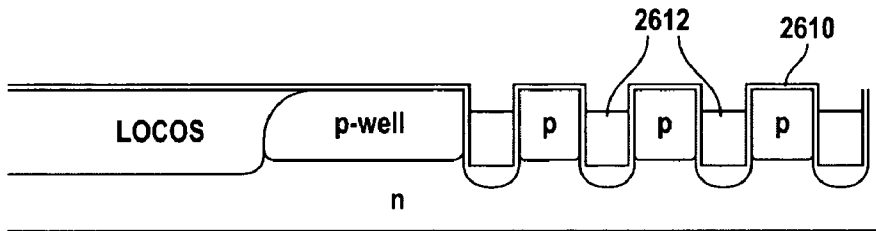


FIG. 24D

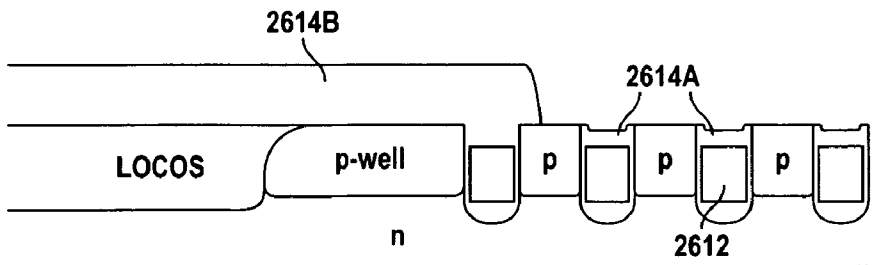


FIG. 24E

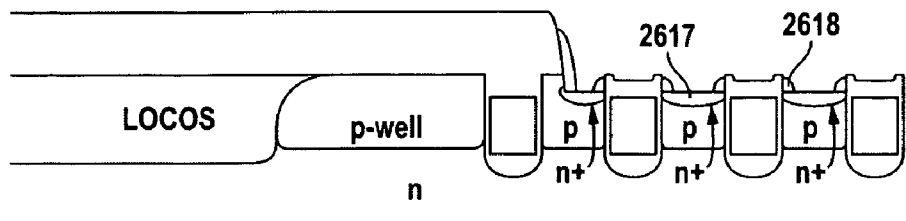


FIG. 24F

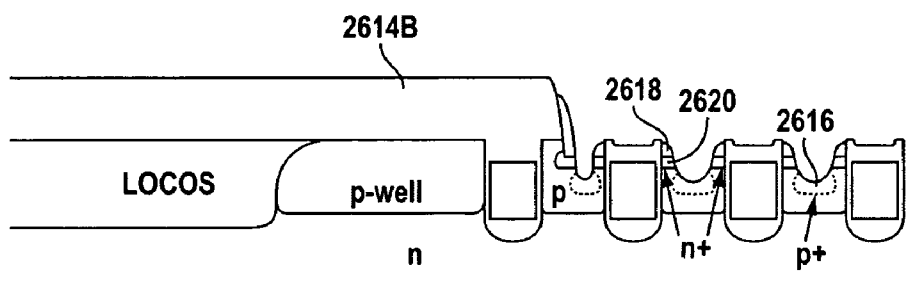


FIG. 24G

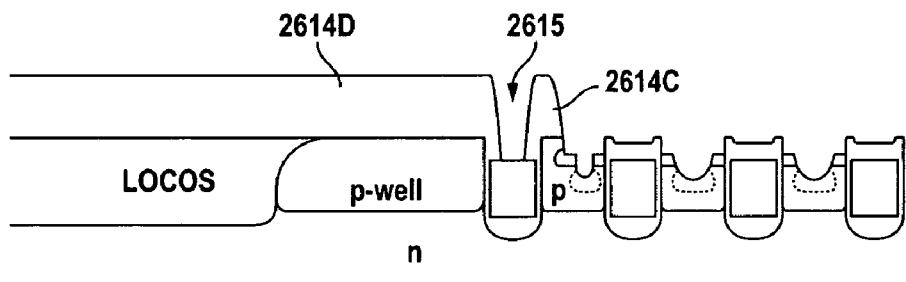


FIG. 24H

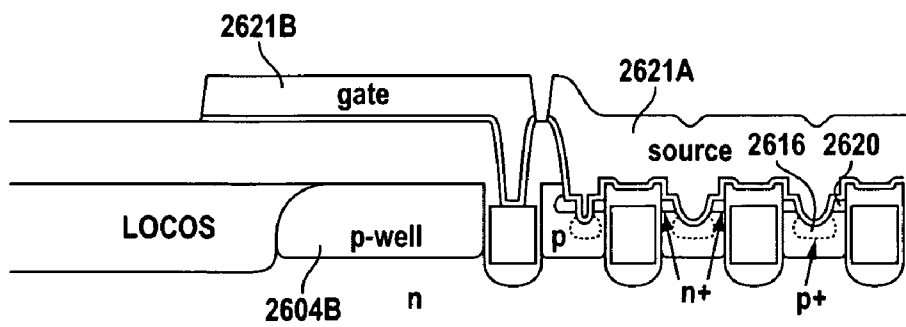


FIG. 24I

**METHOD OF FORMING TRENCH GATE
FIELD EFFECT TRANSISTOR WITH
RECESSED MESAS**

CROSS-REFERENCES TO RELATED
APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 60/669,063, filed Apr. 6, 2005, and is incorporated herein by reference in its entirety for all purposes. The following patent applications are incorporated herein by reference in their entirety for all purposes: U.S. Provisional Application No. 60/588,845, filed Jul. 15, 2004, U.S. application Ser. No. 11/026,276, filed Dec. 29, 2004, and U.S. application Ser. No. 09/844,347, filed Apr. 27, 2001 (Publication No. U.S. 2002/0008284).

BACKGROUND OF THE INVENTION

The present invention relates in general to power semiconductor technology, and more particularly to accumulation-mode and enhancement-mode trench-gate field effect transistors (FETs) and their methods of manufacture.

The key component in power electronic applications is the solid state switch. From ignition control in automotive applications to battery-operated consumer electronic devices, to power converters in industrial applications, there is a need for a power switch that optimally meets the demands of the particular application. Solid state switches including, for example, the power metal-oxide-semiconductor field effect transistor (power MOSFET), the insulated-gate bipolar transistor (IGBT) and various types of thyristors have continued to evolve to meet this demand. In the case of the power MOSFET, for example, double-diffused structures (DMOS) with lateral channel (e.g., U.S. Pat. No. 4,682,405 to Blanchard et al.), trench-gate structures (e.g., U.S. Pat. No. 6,429,481 to Mo et al.), and various techniques for charge balancing in the transistor drift region (e.g., U.S. Pat. No. 4,941,026 to Temple, U.S. Pat. No. 5,216,275 to Chen, and U.S. Pat. No. 6,081,009 to Neilson) have been developed, among many other technologies, to address the differing and often competing performance requirements.

Some of the defining performance characteristics for the power switch are its on-resistance, breakdown voltage and switching speed. Depending on the requirements of a particular application, a different emphasis is placed on each of these performance criteria. For example, for power applications greater than about 300-400 volts, the IGBT exhibits an inherently lower on-resistance as compared to the power MOSFET, but its switching speed is lower due to its slower turn off characteristics. Therefore, for applications greater than 400 volts with low switching frequencies requiring low on-resistance, the IGBT is the preferred switch while the power MOSFET is often the device of choice for relatively higher frequency applications. If the frequency requirements of a given application dictate the type of switch that is used, the voltage requirements determine the structural makeup of the particular switch. For example, in the case of the power MOSFET, because of the proportional relationship between the drain-to-source on-resistance R_{DSon} and the breakdown voltage, improving the voltage performance of the transistor while maintaining a low R_{DSon} poses a challenge. Various charge balancing structures in the transistor drift region have been developed to address this challenge with differing degrees of success.

Two varieties of field effect transistors are accumulation mode FET and enhancement mode FET. In conventional

accumulation FETs because no inversion channel is formed, the channel resistance is eliminated thus improving the transistor power handling capability and its efficiency. Further, with no pn body diode, the losses in synchronous rectification circuits attributable to the pn diode are reduced. A drawback of conventional accumulation transistors is that the drift region needs to be lightly doped to support a high enough reverse bias voltage. However, a lightly doped drift region results in a higher on-resistance and lower efficiency. Similarly, in enhancement mode FETs, improving the transistor break down voltage often comes at the price of higher on-resistance or vice versa.

Device performance parameters are also impacted by the fabrication process. Attempts have been made to address some of these challenges by developing a variety of improved processing techniques. Whether it is in ultra-portable consumer electronic devices or routers and hubs in communication systems, the varieties of applications for the power switch continue to grow with the expansion of the electronic industry. The power switch therefore remains a semiconductor device with high development potential.

BRIEF SUMMARY OF THE INVENTION

The present invention provides various embodiments for power devices, as well as their methods of manufacture. Broadly, According to one aspect of the invention, Schottky diode is optimally integrated with accumulation mode FET or enhancement mode FET in a single cell. According to other aspects of the invention, methods of manufacturing various power transistor structures with self-aligned features as well as other advantages and features are provided.

In accordance with one embodiment of the invention, a monolithically integrated field effect transistor and Schottky diode includes gate trenches extending into a semiconductor region. Source regions having a substantially triangular shape flank each side of the gate trenches. A contact opening extends into the semiconductor region between adjacent gate trenches. A conductor layer fills the contact opening to electrically contact: (a) the source regions along at least a portion of a slanted sidewall of each source region, and (b) the semiconductor region along a bottom portion of the contact opening, wherein the conductor layer forms a Schottky contact with the semiconductor region.

In accordance with another embodiment of the invention, a monolithically integrated trench FET and Schottky diode includes gate trenches extending into and terminating within an epitaxial layer extending over a substrate. Each gate trench has a recessed gate therein with a dielectric material atop the recessed gate. The epitaxial layer being of the same conductivity type as the substrate but having a lower doping concentration than the substrate. Source regions flank each side of the gate trenches, with each source region having a top surface below a top surface of the dielectric material. A contact opening extends into the epitaxial layer between adjacent gate trenches. A conductor layer fills the contact opening to electrically contact the source regions and the epitaxial layer, and to form a Schottky contact with the semiconductor region. The epitaxial layer and the source regions comprise one of silicon carbide, gallium nitride, and gallium arsenide.

In accordance with yet another embodiment of the invention, a monolithically integrated trench FET and Schottky diode includes gate trenches extending into a semiconductor region of a first conductivity type, each gate trench having a recessed gate therein with a dielectric material atop the recessed gate. Source regions of the first conductivity type flank each side of the gate trenches. Each source region has an

upper surface which is recessed relative to an upper surface of the dielectric material atop the corresponding recessed gate. A body region of a second conductivity type extends along each gate trench sidewall between a corresponding source region and the semiconductor region. A contact opening extends into the semiconductor region between adjacent gate trenches. A conductor layer fills the contact opening and electrically contacts the source regions, the body region and the semiconductor region, and the conductor layer forms a Schottky contact with the semiconductor region.

In accordance with another embodiment of the invention, a monolithically integrated trench FET and Schottky diode includes gate trenches extending into a semiconductor region, each gate trench having a gate therein with a dielectric material atop the gate. Semiconductor source spacers flank each side of the gate trenches such that each pair of adjacent semiconductor source spacers located between every two adjacent gate trenches forms a contact opening therebetween. A conductor layer fills the contact openings and contacts the semiconductor source spacers and the semiconductor region, and forms a Schottky contact with the semiconductor region.

In accordance with another embodiment of the invention, a monolithically integrated trench FET and Schottky diode includes gate trenches extending into a semiconductor region of a first conductivity type. Source regions of the first conductivity type flank each side of the gate trenches. A shield electrode is located along a bottom portion of each gate trench, and is insulated from the semiconductor region by a shield dielectric layer. A gate is located over the shield electrode in each trench, and the gate and the shield electrode have a dielectric layer therebetween. A dielectric cap is located over the gate. A conductor layer contacts the source regions and the semiconductor region such that the conductor layer forms a Schottky contact with the semiconductor region.

These and other aspects of the invention are described below in greater detail in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a simplified cross section view of a trench-gate accumulation FET with integrated Schottky in accordance with an exemplary embodiment of the invention;

FIGS. 2A-2I are simplified cross section views depicting various process steps for forming the integrated FET-Schottky diode structure in FIG. 1 according to an exemplary embodiment of the invention;

FIGS. 3A-3E are simplified cross section views depicting alternate process steps to those in the latter portion of the process sequence depicted by FIGS. 2G-2I, according to another exemplary embodiment of the invention;

FIG. 3EE is a simplified cross section view of the an alternate embodiment wherein the dielectric spacers in the process sequence in FIGS. 3A-3E are removed prior to forming the top-side conductor layer;

FIG. 4 is a simplified cross section view of a variation of the structure in FIG. 3EE wherein shield electrodes are formed underneath the gates;

FIG. 5 is a simplified cross section view of a variation of the structure in FIG. 3E wherein the contact openings are extended to about the same depth as the gate trenches;

FIG. 6 is a simplified cross section view of an enhancement mode variation of the accumulation FET-Schottky diode structure in FIG. 5;

FIG. 7A depicts simulation results wherein the electric field lines are shown for two SiC based accumulation FETs one with a deeper Schottky contact recess than the other.

FIG. 7B is a simulated plot of the drain current versus drain voltage for the two cases of deeper and shallower Schottky contact recesses.

FIG. 8 is a simplified cross section view of a trench-gate accumulation FET with polysilicon source spacers, according to an exemplary embodiment of the invention;

FIGS. 9A-9H, 9I-1, and 9J-1 are simplified cross section views depicting various process steps for forming the FET-Schottky diode structure in FIG. 8 in accordance with an exemplary embodiment of the invention;

FIGS. 9I-2 and 9J-2 are simplified cross section views depicting alternate processing steps to the steps corresponding to FIGS. 9I-1 and 9J-1, resulting in a variation of the FET-Schottky diode structure in FIG. 8;

FIGS. 10 and 11 are simplified cross section views respectively illustrating variations of the FET-Schottky structures in FIGS. 9J-1 and 9J-2 wherein shield electrodes are formed underneath the gates;

FIG. 12 is a simplified cross section view of a trench-gate accumulation FET-Schottky structure with shield electrodes underneath the gates in accordance with another embodiment of the invention;

FIG. 13 is a simplified cross section view illustrating a variation of the FIG. 11 embodiment wherein the Schottky region between adjacent trenches is modified to form a MPS structure;

FIG. 14 shows simulated plots of the drain current versus drain voltage characteristics (left plot) and the gate voltage versus the gate charge (right plot) for the FET-Schottky structure in FIG. 1;

FIGS. 15A-15H are simplified cross section views depicting various process steps for forming a trench-gate FET with self-aligned features in accordance with another embodiment of the invention;

FIG. 16 shows an isometric view of a p-channel trench-gate FET with a non-planar top surface (prior to top metal formation) in accordance with another embodiment of the invention;

FIGS. 17A, 17B-1, and 17B-2 are cross section views for two abbreviated process sequences for forming the FET in FIG. 16;

FIG. 18 is cross section view illustrating a technique for forming self-aligned source and heavy body regions, in accordance with an embodiment of the invention;

FIGS. 18A-18I are cross section views at different processing steps for forming the trench-gate FET shown in FIG. 18, in accordance with an exemplary embodiment of the invention;

FIGS. 19A-19H are cross section views at various process steps of a process sequence in which no surface polysilicon is formed and the number of masks is reduced compared to that in the process of FIGS. 18A-18I, in accordance with another exemplary embodiment of the invention;

FIGS. 20A-20G are cross section views depicting another process sequence in which the number of masks is reduced compared to that in FIGS. 18A-18I in accordance with yet another exemplary embodiment of the invention;

FIGS. 21A-21H are cross section views depicting a process sequence for forming a similar trench-gate FET to that resulting from FIGS. 18A-18I except that a Schottky diode is integrated with the FET, in accordance with an exemplary embodiment of the invention;

FIGS. 22A-22F are cross section views depicting yet another process sequence for forming a trench-gate FET with reduced number of masks, in accordance with another embodiment of the invention;

FIGS. 23A-23I are cross section views at different processing steps for forming a trenched-gate FET with self-aligned features, in accordance with yet another embodiment of the invention; and

FIGS. 24A-24I show cross section views at different processing steps for forming a trenched-gate FET with self-aligned features in accordance with yet another embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

The power switch can be implemented by any one of power MOSFET, IGBT, various types of thyristors and the like. Many of the novel techniques presented herein are described in the context of the power MOSFET for illustrative purposes. It is to be understood however that the various embodiments of the invention described herein are not limited to the power MOSFET and can apply to many of the other types of power switch technologies, including, for example, IGBTs and other types of bipolar switches. Further, for the purposes of illustration, the various embodiments of the invention are shown to include specific p and n type regions. It is understood by those skilled in the art that the teachings herein are equally applicable to devices in which the conductivities of the various regions are reversed.

FIG. 1 shows a simplified cross section view of a trenched-gate accumulation field effect transistor (FET) optimally integrated with a Schottky diode in a single cell, in accordance with an exemplary embodiment of the invention. A lightly doped n-type epitaxial layer 104 extends over and is in contact with a highly doped n-type substrate 102. Gate trenches 106 extend into and terminate within epitaxial layer 104. Each gate trench 106 is lined with a dielectric layer 108 along its sidewalls and bottom, and includes a recessed gate 110 and insulating material 112 atop recessed gate 110. Triangular-shaped source regions 114 of n-type conductivity flank each side of trenches 106. Source regions 114 overlap polysilicon gate 110 along the vertical dimension. This overlap is not necessary in such applications as high-voltage FETs wherein the absence of the overlap would have minimal impact on the transistor on-resistance R_{dson} . The absence of the gate-source overlap has more of an impact on R_{dson} in low voltage transistors, and as such its presence would be advantageous in such transistors.

Recessed portions of epitaxial layer 104 together with source regions 114 form V-shaped contact openings 118 with rounded bottoms. A Schottky barrier metal 120 extends over the structure and fills contact openings 118 to make contact with source regions 114 along the sloped sidewalls of source regions 114, and to contact epitaxial layer 104 in the recessed portions thereof. Since source regions 114 are highly doped and epitaxial layer 104 is lightly doped, top-side conductor layer 120 forms an ohmic contact with source regions 114 and a Schottky contact with epitaxial layer 104. In one embodiment, Schottky barrier metal 120 comprises titanium. A back-side conductor layer 122, e.g., comprising aluminum (or titanium), contacts substrate 102.

Unlike enhancement-mode transistors, the accumulation-mode transistor in structure 100 in FIG. 1 does not include a blocking (p-type in this example) well or body region inside which the conduction channel is formed. Instead a conducting channel is formed when an accumulation layer is formed in epitaxial layer 104 along the trench sidewalls. The transistor in structure 100 is normally on or off depending on the doping concentration of the channel region and the doping type of gates 110. It is turned off when the channel regions are entirely depleted and lightly inverted. Also, because no inver-

sion channel is formed, the channel resistance is eliminated thus improving the transistor power handling capability and its efficiency. Further, with no pn body diode, the losses in synchronous rectification circuits attributable to the pn diode are eliminated.

In the FIG. 1 embodiment, the FET in structure 100 is a vertical trenched-gate accumulation MOSFET with the top-side conductor layer 120 forming the source conductor and the bottom-side conductor layer 120 forming the drain conductor. In another embodiment, substrate 102 is p-type thereby forming an accumulation IGBT.

FIGS. 2A-2I are simplified cross section views illustrating various process steps for forming the integrated FET-Schottky diode structure 100 in FIG. 1, in accordance with an exemplary embodiment of the invention. In FIG. 2A, lower epitaxial layer 204 and upper epitaxial layer 205 are sequentially formed over n-type substrate 202 using conventional methods. Alternatively, a starting wafer material which includes epitaxial layers 204, 205 may be used. The upper n-type epitaxial layer 205 has a higher doping concentration than the lower n-type epitaxial layer 204. In FIG. 2B, a mask (not shown) is used to define and etch the silicon to form trenches 206 extending through upper epitaxial layer 205 and terminating within lower epitaxial layer 204 using known techniques. A conventional dry or wet etch may be used in forming the trenches. In FIG. 2C, a dielectric layer 208, e.g., comprising oxide, is grown or deposited over the structure whereby the sidewalls and bottom of trenches 206 are lined with dielectric layer 208.

In FIG. 2D, a layer of polysilicon 209 is then deposited to fill trenches 206 using conventional techniques. Polysilicon layer 209 may be in-situ doped to obtain the desired gate doping type and concentration. In FIG. 2E, polysilicon layer 209 is etched back and recessed within trenches 206 to form gates 210, using conventional techniques. Recessed gates 210 overlap upper epitaxial layer 205 along the vertical dimension. As mentioned above, depending on the target application and the design goals, recessed gates 210 need not overlap upper epitaxial layer 205 (i.e., the process sequence and the final structure need not be limited by this overlap). In other embodiments, gate 210 comprises polysilicon carbide or metal.

In FIG. 2F, a dielectric layer 211, e.g., from oxide, is formed over the structure and then planarized using conventional techniques. In FIG. 2G, a blanket etch of the planarized dielectric layer 211 (in the active region) is carried out at least in the active area of the device to expose surface areas of upper epitaxial layer 205 while portions 212 of dielectric layer 211 remain over recessed gates 210. In FIG. 2H, a blanket angled silicon etch (e.g., dry etch in the active region) is carried out at least in the active area to form the V-shaped contact openings 218 with rounded bottoms using conventional techniques. Contact openings 218 extend clear through upper epitaxial layer 205 thus forming two source regions 214 between every two adjacent trenches. Contact openings 218 extend into and terminate within an upper half of lower epitaxial layer 204.

In FIG. 2I, top-side conductor layer 220 is formed using conventional techniques. Top-side conductor layer 220 comprises a Schottky barrier metal. As shown, top-side conductor layer 220 fills contact openings 218 so as to make contact with source regions 214 along the slanted sidewalls of source regions 214, and with lower epitaxial layer 204 along the bottom of contact openings 218. Since source regions 214 are highly doped and lower epitaxial layer 204 is lightly doped, top-side conductor layer 220 forms an ohmic contact with source regions 214, and forms a Schottky contact with lower

epitaxial layer **204**. As can be seen, source regions **214** and the Schottky contacts are self-aligned to trenches **206**.

FIGS. **3A-3E** are simplified cross section views depicting alternate process steps to those in the latter portion of the process sequence depicted by FIGS. **2G-2I**, according to another exemplary embodiment of the invention. Thus, in this embodiment, the same process steps depicted by FIGS. **2A** through **2G** are carried out leading to the step depicted by FIG. **3B** (the step depicted by FIG. **3A** is the same as the step depicted by FIG. **2G**). In FIG. **3B**, upper epitaxial layer **305** is etched back to expose upper sidewalls of dielectric material **312** sufficiently to accommodate the subsequent formation of dielectric spacers **316**. In one embodiment, second epitaxial layer **305** is etched back by an amount in the range of 0.05-0.5 μm . In FIG. **3C**, spacers **316** are formed adjacent to the exposed upper sidewalls of dielectric material **312** using conventional techniques. Spacers **316** are from a dielectric material different than that of dielectric material **312**. For example, if dielectric material **312** is from oxide, spacers **316** may be from nitride.

In FIG. **3D**, the exposed surface areas of upper epitaxial layer **305** are recessed clear through epitaxial layer **305** thus forming contact openings **318** which extend into lower epitaxial layer **304**. By recessing clear through upper epitaxial layer **305**, only portions **314** of upper epitaxial layer **305** directly below spacers **316** remain. Portions **314** form the transistor source regions. As can be seen, contact openings **318** and thus source regions **314** are self-aligned to trenches **306**. In FIG. **3E**, top-side conductor layer **320** and bottom-side conductor layer **322** are formed using conventional techniques. Conductor layer **320** comprises a Schottky barrier metal. As shown, top-side conductor **320** fills contact openings **318** so as to make contact with source regions **314** along sidewalls of source regions **314**, and with the recessed portions of lower epitaxial layer **304**. Since source regions **314** are highly doped and lower epitaxial layer **304** is lightly doped, top-side conductor layer **320** forms an ohmic contact with source regions **314**, and forms a Schottky contact with lower epitaxial layer **304**.

In an alternate embodiment shown in FIG. **3EE**, prior to forming the top-side conductor layer, dielectric spacers **316** are removed thus exposing the top surfaces of source regions **314**. Top-side conductor layer **321** thus makes contact along the top surface and sidewalls of source regions **314**. The source contact resistance is thus reduced. In an alternate variation of the various embodiments described above, known techniques are used to form a thick bottom dielectric along the bottom of each trench before forming the gates. The thick bottom dielectric reduces the miller capacitance.

As can be seen from the various embodiments described herein, a Schottky diode is optimally integrated with a FET in a single cell which is repeated many times in an array of such cells. Also, the Schottky contact and the source regions are self-aligned to the trenches. Further, the Schottky contact results in lower on resistance R_{dson} and thus lower on-state losses, and also improves the transistor reverse recovery characteristics. Good blocking capability is also obtained without the need for a tight cell pitch.

In the exemplary process sequences depicted by FIGS. **2A-2I** and FIGS. **3A-3E** no diffusion or implantation processes are used. While these process sequences can be used with conventional crystalline silicon material, they are particularly suitable for use with such other types of materials as silicon carbide (SiC), gallium nitride (GaN), and gallium arsenide (GaAs) where diffusion, implantation, and dopant activation processes are difficult to accomplish and control. In such embodiments, the substrate, the lower and upper epi-

taxial layers, as well as other regions of the transistor may comprise one of SiC, GaN, and GaAs. Further, in conventional silicon carbide based enhancement mode FETs, the contribution of the inversion channel to the on resistance is particularly high. In contrast, the contribution to the on resistance of the accumulated channel in the silicon carbide embodiment of the accumulation transistors in FIGS. **2I** and **3E** is substantially low.

FIG. **4** shows a cross section view of another embodiment of the present invention. In FIG. **4**, shield electrodes **424** are formed below gates **410**. Shield electrode **424** is insulated from lower epitaxial layer **404** by a shield dielectric **425**, and is insulated from the overlying gate **410** by an inter-electrode dielectric **427**. Shield electrodes **424** help reduce miller capacitance to a negligible amount and thereby drastically reduce transistor switching losses. Though not shown in FIG. **4**, shield electrodes **424** are electrically connected to source regions **414**, or to the ground potential, or to other potentials as the design and performance requirements dictate. More than one shield electrode biased to the same or different potentials may be formed below each gate **410** if desired. One or more methods for forming such shield electrodes are disclosed in the above-referenced commonly assigned application Ser. No. 11/026,276. Also, other charge balance structures disclosed in application Ser. No. 11/026,276 may be combined with the various embodiments disclosed herein to further improve the performance characteristics of the device.

A limitation of some conventional silicon carbide based trenched-gate transistors is the low gate oxide breakdown voltage. In accordance with the invention, this problem is addressed by extending the Schottky contact recess deeper, e.g., to a depth greater than one half of the depth of the gate trenches. FIG. **5** shows an exemplary embodiment wherein the Schottky contact recess is extended to approximately the same depth as gate trenches **506**. The deep Schottky contact serves to shield gate oxide **508** from high electric fields and thus improves the gate oxide breakdown. This can be seen in FIG. **7A** which shows simulation results for two SiC based accumulation FETs one of which has a deeper Schottky contact recess. The electric field lines present along the bottom of the trench in the transistor with a shallower Schottky contact recess (right diagram) are eliminated in the transistor with a deeper Schottky contact recess case (left diagram). The electric field lines below the gate trench in the right diagram reflect increasing electric field from bottom to top. That is, the lowest-most electric field line corresponds to the highest electric field and the upper-most electric field line corresponds to lowest electric field.

A further advantage of the deep Schottky contact recess is reduction in transistor leakage in the blocking state. This is more clearly shown in the simulation results in FIG. **7B** wherein the drain current versus drain voltage is plotted for a deeper Schottky contact recess versus a shallower Schottky contact recess. As can be seen, as the drain voltage is increased from 0 V to 200 V, the drain current continuously rises in the case of shallower Schottky contact recess while the drain current remains flat for the deeper Schottky contact recess. Thus, a substantial reduction in transistor leakage as well as a higher gate oxide breakdown is achieved by recessing the Schottky contact deeper into epitaxial layer **504**.

The deeply recessed Schottky contact structure (e.g., that in FIG. **5**) is particularly suitable in the silicon carbide based transistors because the gate trenches need not extend as deep in the epitaxial layer as compared to the silicon based transistors. This allows shallower Schottky contact recesses which are easier to define and etch. However, similar improvements in gate oxide breakdown and transistor leak-

age can be obtained for similar structures using other types of material such as SiC, GaN and GaAs.

FIG. 6 shows an enhancement mode FET variation of the accumulation FET in the FIG. 5 structure. In FIG. 6, a p-type body region 613 extends along each trench sidewall directly below a corresponding source region 614. As shown, the deep contact openings 618 extends below a bottom surface of body regions 613 to enable formation of the Schottky contact between top-side conductor layer 620 and N-epitaxial layer 604. As in conventional MOSFETs, when the MOSFET in FIG. 6 is in the on state, a current flows through a channel extending along each trench sidewall in body regions 613. In a variation of the FIG. 6 embodiment, spacers 616 are removed so that top-side conductor layer 620 contacts source regions 614 along their top surface.

FIG. 8 shows a cross section view of an accumulation mode FET with spacer source regions optimally integrated with a Schottky diode in a single cell, in accordance with another exemplary embodiment of the invention. An n-type epitaxial layer 1104 extends over and is in contact with an n-type substrate 1102. Gate trenches 1106 extend into and terminate within epitaxial layer 1104. Each gate trench 1106 is lined with a dielectric layer 1108 along its sidewalls and bottom, and includes a gate 1110 and insulating material 1112 atop gate 1110. Spacer source regions 1114 of n-type material, for example, n-type polysilicon, are over epitaxial layer 1104 and flank each side of trenches 1106.

Spacer source regions 1114 form contact openings 1118 through which a top-side conductor layer 1120 electrically contacts both epitaxial layer 1104 and source regions 1114. Top-side conductor layer 1120 comprises Schottky barrier metal. Since epitaxial layer 1104 is lightly doped, top-side conductor layer 1120 forms a Schottky contact with epitaxial layer 1104.

As in previous embodiments, the accumulation-mode transistor in structure 1100 does not include a blocking (p-type in this example) well or body region inside which the conduction channel is formed. Instead a conducting channel is formed when an accumulation layer is formed in epitaxial layer 1104 along trench sidewalls. The FET in structure 1100 is normally on or off depending on the doping concentration of the channel region and the doping type of gates 1110. It is turned off when channel regions are entirely depleted and lightly inverted. Also, because no inversion channel is formed, the channel resistance is eliminated thus improving the transistor power handling capability and its efficiency. Further, with no pn body diode, the losses in synchronous rectification circuits attributable to the pn diode are eliminated.

In the FIG. 8 embodiment, the FET in structure 1100 is a vertical trench-gate accumulation MOSFET with the top-side conductor layer 1120 forming the source conductor and the bottom-side conductor layer (not shown) forming the drain conductor. In another embodiment, substrate 1102 may be p-type to form an accumulation IGBT.

FIGS. 9A to 9H, 9I-1, and 9J-1 show cross section views at different processing steps for forming the integrated FET/Schottky diode structure 1100 in FIG. 8 in accordance with an embodiment of the invention. In FIG. 9A, n-type epitaxial layer 1204 is formed over n-type substrate 1202 using conventional methods. Alternatively, a starting wafer which includes epitaxial layer 1204 may be used. In FIG. 9B, a mask (not shown) is used to define and etch silicon to form trenches 1206 using conventional techniques. A conventional dry or wet etch may be used in forming the trenches. Trenches 1206 extend through and terminate within epitaxial layer 1204. In FIG. 9C, a dielectric layer 1208, e.g., comprising oxide, is

grown or deposited over the structure such that the sidewalls and bottom of trenches 1206 are lined with dielectric layer 1208.

In FIG. 9D, a layer of polysilicon 1209 is deposited to fill trenches 1206 using conventional techniques. Polysilicon layer 1209 may be in-situ doped to obtain the desired gate doping type and concentration. In FIG. 9E, polysilicon layer 1209 is etched back and recessed within trenches 1206 to form recessed gates 1210 using conventional techniques.

In FIG. 9F, a dielectric layer 1211, e.g., comprising oxide, is formed over the structure and then planarized using conventional techniques. In FIG. 9G, a blanket etch of the planarized dielectric layer 1211 (at least in the active region) is carried out to expose surface areas of epitaxial layer 1204 while portions 1212 of dielectric layer 1211 remain over gates 1210. In FIG. 9H, epitaxial layer 1204 is etched back exposing sidewalls of dielectric material 1212 sufficiently to accommodate the subsequent formation of source spacers 1214. In FIG. 9I-1, a conductive layer, e.g., polysilicon, is deposited and then etched back to form highly-doped source spacers 1214 adjacent to the exposed sidewalls of dielectric material 1212. Where polysilicon is used to form source spacers 1214, the polysilicon may be in-situ doped to obtain highly doped source spacers. In FIG. 9J-1, a top-side conductor layer 1220 is formed using conventional techniques. Conductor layer 1220 comprises Schottky barrier metal. In one embodiment, conductor layer 1220 comprises titanium. As shown, source spacers 1214 form contact openings 1218 through which top-side conductor layer 1220 contacts epitaxial layer 1204. Conductor layer 1220 also contacts source spacers 1214. Since source spacers 1214 are highly doped and epitaxial layer 1204 is lightly doped, top-side conductor layer 1220 forms an ohmic contact with source spacers 1214 and a Schottky contact with epitaxial layer 1204.

FIGS. 9I-2 and 9J-2 are cross section views depicting alternate processing steps to the steps depicted by FIGS. 9I-1 and 9J-1, resulting in a variation of the structure in FIG. 8. In contrast to the step in FIG. 9I-1 wherein the polysilicon etch is stopped when the surface of epitaxial layer 1204 is exposed, in the step shown in FIG. 9I-2, the polysilicon etch is continued to recess the exposed epitaxial layer regions between the source spacers. As can be seen, because of the additional etch, source spacers 1215 in FIG. 9I-2 are smaller than source spacers 1214 in FIG. 9I-1. In FIG. 9J-2, a top-side conductor layer 1221 is formed over the structure using conventional methods. Top-side conductor layer 1221 forms an ohmic contact with source spacers 1215 and a Schottky contact with epitaxial layer 1204 in regions 1219.

As can be seen, the Schottky contact and source spacers are self-aligned to trenches 1406. Further, the Schottky contact results in lower on resistance R_{dson} and thus lower on-state losses, and also improves the transistor reverse recovery characteristics. Also, good blocking capability is achieved without the need for a tight cell pitch. Moreover, as described in connection with the FIG. 7 diagram, a further advantage of the recessed Schottky contact of the FIGS. 9I-2, 9J-2 embodiment is reduction in transistor leakage in the blocking state. Also, the polysilicon source spacers consume a smaller area than the conventional diffused source regions. This advantageously results in a larger Schottky contact area.

FIG. 10 shows a cross section view of a variation of the FIG. 8 embodiment wherein shield electrodes 1324 are formed below gates 1310. Shield electrodes 1324 help reduce miller capacitance to a negligible amount and thereby drastically reduce transistor switching losses. Shield electrodes 1324 may be electrically biased to the same potential as the source spacers, or to the ground potential, or to other poten-

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tials as the design and performance requirements dictate. More than one shield electrode biased to the same or different potentials may be formed below each gate 1310 if desired. One or more methods for forming such shield electrodes are disclosed in the above-referenced commonly assigned application Ser. No. 11/026,276.

The advantages in using a recessed Schottky contact and in using shield electrodes may be realized by combining them in a single structure as shown by the two examples in FIGS. 11 and 12. FIG. 11 shows use of the recessed Schottky contact and the shield electrode in an accumulation mode FET with polysilicon source spacers 1415. FIG. 12 shows use of the recessed Schottky and shield electrode in an accumulation mode FET with source regions 1517 formed using conventional diffusion methods. FIG. 13 shows a variation of the FIG. 11 embodiment wherein the Schottky region is modified to incorporate p-type regions 1623. P-type regions 1623 may be formed by implanting p-type dopants in the Schottky region prior to forming top-side conductor layer 1620. The well-known Merged P-i-N Schottky (MPS) structure is thus formed in the region between adjacent trenches. In effect, a blocking junction is introduced in an accumulation transistor. As is well understood in this art, the MPS structure reduces the transistor leakage when in blocking state.

FIG. 14 shows simulation results using the structure in FIG. 1. MEDICI device simulator was used. FIG. 14 includes a left diagram wherein the drain current versus the drain voltage is plotted, and a right diagram wherein the gate voltage versus gate charge is plotted. As the left plot shows, a low leakage current of 1×10^{-14} Amperes/ μm and a BVDSS of greater than 35 V are obtained, and as the right plot shows, the shield electrodes help eliminate the miller capacitance.

In the exemplary process sequences depicted by FIGS. 9A-9H, 9I-1, 9J-1, 9I-2, and 9J-2 and the exemplary transistor structures in FIGS. 10 and 11 no diffusion or implantation processes are used. While these process sequences and structures can be used with conventional crystalline silicon material, they are particularly suitable for use with such other types of materials as silicon carbide (SiC), gallium nitride (GaN), gallium arsenide (GaAs) where diffusion, implantation, and dopant activation processes are difficult to accomplish and control. In such embodiments, the substrate, the epitaxial layer over the substrate, the source regions, as well as other regions of the transistor may be from one of SiC, GaN, and GaAs. Further, in conventional silicon carbide based enhancement mode FETs, the contribution of the inversion channel to the on resistance is particularly high. In contrast, the contribution to the on resistance of the accumulated channel in the silicon carbide embodiment of the accumulation transistors in FIGS. 9J-1, 9J-2, 10, and 11 is substantially low.

While the above embodiments are described using mostly accumulation mode FETs, many of the above features and advantages may be realized in enhancement mode FETs. For example, the process sequences in FIGS. 2A-2I and 3A-3E may be modified by forming p-type well regions in lower epitaxial layer 204 prior to forming upper epitaxial layer 205. The process sequences in FIGS. 9A-9H, 9I-1, 9J-1, and 9A-9H, 9I-2 and 9J-2 may also be modified by forming p-type well regions in epitaxial layer 1204 prior to forming source spacers 1214 and 1215. Many other ways of modifying the above described structures and process sequence embodiments in order to obtain enhancement mode FETs integrated with Schottky diode would be obvious to one skilled in the art in view of this disclosure.

FIGS. 15A-15H are simplified cross section views at different processing steps for forming a trench-gate FET in accordance with another embodiment of the invention. In

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FIG. 15A, lightly doped p-type body region 1704 is formed in n-type region 1702 using conventional implant and drive techniques. In one embodiment, n-type region 1702 comprises a highly doped substrate region over which a lower doped n-type epitaxial layer is formed. In such embodiment, body region 1704 is formed in the n-type epitaxial layer.

In FIG. 15B, a dielectric stack comprising a lower dielectric layer 1706, a middle dielectric layer 1708, and an upper dielectric layer 1710 is formed over body region 1704. The middle dielectric layer is required to be of a different dielectric material than the upper dielectric material. In one embodiment, the dielectric stack comprises oxide-nitride-oxide. As will be seen, the thickness of the middle dielectric layer 1708 impacts the thickness of a dielectric cap 1720 (FIG. 15D) formed over the gate in a later step of the process, and thus must be carefully selected. The lower dielectric layers is relatively thin in order to minimize the reduction in thickness of dielectric layer 1720 during removal of lower dielectric layer 1706 in a later step of the process. As shown, the dielectric stack is patterned and etched to define opening 1712 through which a gate trench is later formed.

In FIG. 15C, a conventional silicon etch is carried out to form a trench 1703 extending through body region 1704 and terminating in n-type region 1702. A gate dielectric layer 1714 lining the trench sidewalls and bottom is then formed followed by deposition of a polysilicon layer 1716 using conventional techniques. In FIG. 15D, polysilicon layer 1716 is recessed into the trench to form gate 1718. A dielectric layer is formed over the structure and then etched back such that dielectric cap 1720 remains directly above gate 1718. Nitride layer 1708 serves as an etch stop or etch stop detection layer during the etch back of the dielectric layer. In FIG. 15E, nitride layer 1708 is selectively stripped to expose sidewalls of dielectric cap 1720, using know techniques. The bottom oxide layer 1706 thus remains over body region 1704, and dielectric cap 1720 also remains intact over gate 1718.

In FIG. 15F, a blanket source implant is carried out in the active region of the device to form highly doped n-type regions 1722 in body regions 1704 on either sides of trench 1703. Dielectric spacers 1724 (e.g., comprising oxide) are then formed along the exposed sidewalls of dielectric cap 1720 using conventional techniques. The activation and drive-in of the implanted dopants can be carried out at this or a later stage of the process sequence. In FIG. 15G, a silicon etch is carried out to recess the exposed surfaces of n-type regions 1722 clear through n-type regions 1722 and into body regions 1704 as shown. Portions 1726 of n-type regions 1722 remaining directly under spacers 1724 form the source regions of the device. Heavy body regions 1728 are then formed in the recessed regions. In one embodiment, heavy body regions 1728 are formed by filling the etched silicon with p-type silicon using conventional silicon epitaxial growth. Heavy body regions 1728 and source regions 1726 are thus self-aligned to trench 1703.

In FIG. 15H, dielectric cap 1720 and spacers 1724 are then partially etched back to expose surface areas of source regions 1726. After the etch, domed dielectric 1730 remains over gate 1718. Top conductor layer 1732 is then formed to contact source regions 1726 and heavy body regions 1728. Domed dielectric 1730 serves to electrically insulate gate 1718 from top conductor layer 1732. In one embodiment, n-type region 1702 is a lightly doped epitaxial layer with a highly doped n-type substrate (not shown) extending below the epitaxial layer. In this embodiment, a back side conductor layer (not shown) is formed to contact the substrate, the back

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side conductor layer forming the device drain terminal. A trenched-gate FET with self-aligned source and heavy body regions is thus formed.

In an alternate embodiment, a thick dielectric layer (e.g., comprising oxide) is formed along a bottom portion of trench **1703** before forming gate **1718**. The thick bottom dielectric has a greater thickness than gate dielectric **1714**, and serves to reduce the gate to drain capacitance thus improving the device switching speed. In yet another embodiment, a shield electrode is formed below gate **1718** similar to those shown in FIGS. **4** and **10-13**.

In yet another variation of the process sequence depicted by FIGS. **15A-15H**, after the steps corresponding to FIG. **15F**, the exposed silicon surfaces are not recessed, and instead a heavy body implant and drive-in process is carried out to form heavy body regions extending through n-type regions **1722** and into body regions **1704**. A similar cross section view to that in FIG. **15G** is obtained except that heavy body regions **1728** extend under dielectric spacers **1724** due to side diffusion during the drive-in process. Dielectric spacers **1724** need to be wide enough to ensure that the n-type region **1722** is not entirely consumed during side diffusion of the heavy body region. This can be achieved by selecting a thicker middle dielectric layer **1708**.

The technique of using a dielectric stack to obtain self-aligned source and heavy body regions as illustrated in FIGS. **15A-15H** can be similarly implemented in a number of the process embodiments disclosed herein. For example, in the process embodiment depicted by FIGS. **3A-3E**, the process steps corresponding to FIGS. **3A-3B** may be replaced with the process steps depicted by FIGS. **15B-15E** in order to obtain self-aligned source regions and Schottky contacts, as described next.

The mask used to form trenches **306** in FIG. **3A** is replaced with a dielectric stack of three dielectric layers which is patterned and etched to form openings through which trenches are formed (similar to that shown in FIGS. **15B** and **15C**). Then, in FIG. **3B**, with the opening in the ONO composite layer filled with a dielectric cap (similar to dielectric cap **1720** in FIG. **15D**), the top oxide and the intermediate nitride layer of the ONO composite layer are removed to expose sidewalls of the dielectric cap (similar to that shown in FIG. **15E**). The remainder of the process sequence depicted by FIGS. **3C-3E** remains unchanged. Recessing of n+ epi layer **305** carried out in FIG. **3B** in order to expose sidewalls of dielectric **312** is no longer necessary, and a thinner epitaxial layer **305** may be used.

The dielectric stack technique may also be implemented in the process embodiment depicted by FIGS. **9A-9J** by replacing the process steps corresponding to FIGS. **9B-9** with the process steps depicted by FIGS. **15B-15E** in a similar manner to that described above.

FIG. **16** shows a simplified isometric view of a p-channel trenched-gate FET having a non-planar top surface (prior to top metal formation) in accordance with another embodiment of the invention. This invention is not limited to p-channel FETs. One skilled in this art would know how to implement the invention in an n-channel FET or other types of power transistors in view of this disclosure. In FIG. **16**, top metal layer **1832** is peeled back to reveal the underlying regions. Similarly, dielectric caps **1820** are partially removed from over the right two gates **1818** for illustration purposes. As shown, a lightly-doped n-type body region **1804** extends over a lightly doped p-type region **1802**. In one embodiment, p-type region **1802** is an epitaxial layer formed over a highly doped p-type substrate (not shown), and body region **1804** is

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formed in epitaxial layer **1802** by implanting and driving in appropriate dopants as know in this art.

Gate trenches **1806** extend through body region **1804** and terminate in p-type region **1802**. Each gate trench **1806** is lined with a gate dielectric **1805** and then filled with polysilicon which is recessed relative to a top surface of the adjacent silicon mesa regions. A dielectric cap **1820** extends vertically over each gate **1818**. Heavily doped p-type source regions **1826** are formed in body region **1804** between adjacent trenches. As shown, a top surface of dielectric cap **1820** is at a higher plane than the top surface of source regions **1826**, resulting in a non-planar top surface. In one embodiment, this non-planarity is obtained by recessing the silicon mesa between dielectric caps **1820**. Heavy body regions **1828** are intermittently formed along the stripe-shaped body regions **1804** between adjacent trenches. A top side metal layer **1832** is formed over the structure to make electrical contact to both source regions **1826** and heavy body regions **1828**. This FET structure is advantageous in that the cell pitch is reduced by forming the heavy body region intermittently along the source stripe, and thus a high density FET is achieved.

FIGS. **17A**, **17B-1**, and **17B-2** will be used to describe two ways of forming the FET in FIG. **16**. These figures do not show the heavy body regions because these figures correspond to cross section views along the front face of the isometric view in FIG. **16**. In FIG. **17A**, n-type body region **1904** is formed in p-type epitaxial layer **1902** using conventional implant and drive-in techniques. Trenches **1906**, gate insulator **1907** lining trenches **1906**, and the recessed polysilicon gates **1918** are formed using known techniques. A dielectric layer is formed over the structure, is then planarized, and finally uniformly etched back until the silicon surface is exposed. The space directly over each gate is thus filled with dielectric cap **1920**. In one embodiment, the exposed silicon mesa surfaces between adjacent dielectric regions **1920** are recessed to a depth intermediate the top and bottom surfaces of dielectric region **1920**, followed by a source implant to form p-type source regions. In an alternate embodiment, the source formation is carried out before recessing the silicon. The heavy body regions (not shown) can be formed before or after forming the source regions.

FIG. **17B-1** shows a variation wherein the silicon recess is carried out so that upper sidewalls of dielectric regions **1920** become exposed (i.e., source regions **1926** have flat top surfaces). FIG. **17B-2** shows another variation wherein the silicon recess is carried out so that the top surface of the source regions between adjacent trenches is bowl-shaped and thus sidewalls of dielectric regions **1920** are not exposed. In one embodiment, this is achieved by performing an anisotropic silicon etch. An advantage of the FIG. **17B-2** variation is that a larger source surface area is provided for contact with the top conductor layer **1935**, and thus the source contact resistance is reduced. Also, a tighter cell pitch and thus a high density FET is obtained by forming the heavy body regions intermittently along the source stripes.

FIG. **18** is a simplified cross section depicting a technique for obtaining a highly compact trenched-gate FET with self-aligned heavy body and source regions. In FIG. **18**, gate trenches with gates **2012** therein extend through p-well region **2004** and terminate within n-type drift region **2000**. In one embodiment, n-type drift region **2000** is an epitaxial layer formed over a highly doped n-type substrate (not shown). Each gate trench includes a dielectric cap **2014** over gate **2012**. As shown, the mesa regions between the two trenches is recessed such that the silicon recess has sloped outer walls extending from near the top of dielectric cap **2014** to the bottom of the mesa recess.

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As indicated by the solid line arrow **2019** extending perpendicularly to the bottom surface of the mesa recess, highly doped p-type heavy body region **2016** is formed by carrying out a blanket implant of dopants (e.g., BF_2) at a zero degree angle. Given the zero degree angle of the heavy body implant, the opposite slopes of each trench sidewall and its immediately adjacent outer wall of the mesa recess, together with careful selection of the implant dopant type and such implant variables as implant energy, ensure that the implanted dopants do not reach the channel regions extending along the trench sidewalls in well regions **2004**.

As indicated by the two angled dashed line arrows **2018**, a blanket two-pass angled implant of n-type dopants is performed to form source regions **2020** along the sloped walls of each mesa recess. As shown, the upper trench corners block the source implants from entering the central portion of the heavy body region. As can be seen no mask is used during either the heavy body implant or the two-pass angled source implant. The mesa recess, in effect, creates a natural mask enabling formation of self-aligned heavy body and source regions.

The self-aligned heavy body and source regions enable a significant reduction in the cell pitch resulting in a highly dense cell structure which in turn helps reduce the transistor on-resistance. Further, self-aligned heavy body regions help improve the unclamped inductive switching (UIL) ruggedness. Also, forming the source and heavy body regions in a self-aligned manner, reduces the number of masks thus reducing the manufacturing cost while simplifying the process sequence and improving manufacturing yield. Moreover, the particular profile of the source and heavy body regions are advantageous in that: (i) the sloped outer walls the mesa recess provides a large source surface area which helps reduce the source contact resistance, and (ii) the heavy body region overlaps under the source regions which helps improve the transistor UIL ruggedness. Further, as will be seen, the technique illustrated in FIG. **18** is compatible with many thick bottom dielectric processes, and lends itself well to the LOCOS process.

FIGS. **18A-18I**, **19A-19H**, **20A-20G**, **21A-21H**, and **22A-22F** show various process sequences wherein the technique illustrated in FIG. **18** is used to form various FET structures with self-aligned features. Many other process sequences or variations of those disclosed herein with the technique illustrated in FIG. **18** implemented therein can be envisioned by one skilled in this art in view of this disclosure.

FIGS. **18A-18I** show cross section views at different processing steps for forming a trenched-gate FET with self-aligned source and heavy body regions in accordance with another embodiment of the invention. In FIG. **18A**, conventional silicon etch and LOCOS processes are used to form insulation-filled trench **2001** in the termination region. A pad oxide layer (not shown) and a nitride layer (not shown) are first formed over n-type silicon region **2000**. A first mask is then used to define the portion of silicon region **2000** in the termination region where silicon is to be removed. The nitride layer, pad oxide and the underlying silicon region are removed through the first mask to form trench **2001** in the termination region. Local oxidation is then carried out to fill trench **2001** with insulating material **2002**. Although not shown, the starting material may comprise a highly doped n-type substrate over which n-type region **2000** is formed, for example, epitaxially.

In FIG. **18B**, a blanket well implant and drive-in is carried out to form p-type well region **2004** in silicon region **2000**. The implanted impurities may alternatively be driven in at a later stage of the process. In FIG. **18C**, a second masking step

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is carried out to define and etch trenches **2006** which extend through well region **2004** and terminate within silicon region **2000**. A bottom portion of trenches **2006** is filled with insulating material by, for example, depositing high density plasma (HDP) oxide and then etching the deposited HDP oxide to form thick bottom oxide **2008**.

In FIG. **18D**, a gate insulating layer **2010** is formed along all surface areas including the trench sidewalls. Polysilicon is then deposited and doped (e.g., in situ). A third mask is used to define and etch the polysilicon to form recessed gates **2012A** in the active area, termination trench gate **2012B** and the surface gate **2012C**. In FIG. **18E**, a dielectric layer is formed over the structure. A fourth mask is then used to define the portion of the active region and the opening **2015** in the termination region where the dielectric layer is to be etched back. The dielectric layer is etched through the mask openings until silicon is reached. Thus, in the active region, the space directly over each gate **2012A** remains filled with dielectric material **2014A**, while opening **2015** is formed in the termination region. As can be seen, surfaces of well regions **2004B** in the active region and well region **2004A** in the termination region are exposed.

In FIG. **18F**, a silicon etch step is carried out to recess the exposed silicon surface areas in the active and termination regions. An almost bowl-shaped silicon surface is formed in well regions **2004B** between adjacent trenches in the active region and in well region **2004A** in the termination region. Next, a zero degree heavy body implant (e.g., BF_2) is carried out to form p-type heavy body regions **2016B** in well regions **2004B** of the active region, and to form heavy body region **2016A** in well region **2004A** of the termination region. Source regions **2020** are then formed using a two-pass angled source implant as depicted by arrows **2018**. In the two-pass angled implant, n-type impurities are implanted at such angle that the upper trench corners prevent a central portion **2016B** of the heavy body regions from receiving the implant. Source regions **2020** are thus formed immediately adjacent the trenches while a central portion **2016B** of the heavy body regions remains intact as shown. Because of the aspect ratio of the opening **2015** (FIG. **18E**) and the angle of the two-pass source implant, termination well region **2004A** does not receive the source implants.

In FIG. **18G**, an implant activation step is carried out to drive in the implanted dopants. A fifth mask is then used to define and etch insulating layer **2014C** to form gate contact opening **2019**. In FIG. **18H**, a conductor layer (e.g., comprising metal) is then formed over the structure. A sixth mask is used to define and etch the conductor layer in order to isolate source conductor **2021A** from gate conductor **2021B**. In FIG. **18I**, a passivation layer is deposited. A seventh mask is then used to etch portions of the passivation layer to thereby define source and gate areas where wirebond contacts are to be made. In embodiments wherein a passivation layer is not necessary, the corresponding mask and process steps are eliminated.

As can be seen no mask is used in forming heavy body regions **2016B** and source regions **2020**. Also, both the heavy body and source regions are self-aligned with the trench edges. Further, heavy body region **2016B** overlaps beneath source regions **2020** but does not extend into the channel regions. A tight cell pitch with an exceptional snapback and UIL ruggedness is thus achieved. The small cell pitch helps achieve a lower R_{dson} . Also, since source regions **2020** are formed along the outer curved surfaces of well regions **2004B**, a larger source contact area is obtained and thus a lower source contact resistance is achieved. Moreover, the simple process sequence uses a reduced number of masking

steps, is compatible with many thick bottom oxide (TBO) process modules, and lends itself well to the LOCOS method of forming the TBO.

The cross sections in FIGS. 18A-18I depict merely an exemplary process sequence and an exemplary termination structure. This process sequence may be optimized in various ways to further reduce the number of masks and implement different termination structures including those illustrated by the process sequences in FIGS. 19A-19H, 20A-20G, 21A-21H, and 22A-22F described next.

FIGS. 19A-19H are cross section views of a process sequence in which instead of a surface polysilicon a trenched polysilicon is formed which enables reducing the number of masks by one compared to that in the process of FIGS. 18A-18I. The process steps corresponding to FIGS. 19A-19C are similar to those corresponding to FIGS. 18A-18C and thus will not be explained. In FIG. 19D, gate insulator 2110 is formed and then polysilicon is deposited and doped. A blanket etch of the deposited polysilicon is carried out so that recessed gates 2112 remain in the trenches. Here, the gate mask in FIG. 18D of the previous embodiment is eliminated. In FIG. 19E, a similar sequence of process steps to that in FIG. 18E is carried out so that the space directly over each gate 2112 is filled with dielectric material 2114A, while opening 2115 is formed in the dielectric layer over termination p-well 2014A. In FIG. 19F, a similar sequence of process steps to that in FIG. 18F is carried out to form self-aligned heavy body regions 2116A and 2116B and self-aligned source regions 2120.

In FIG. 19G, a gate contact mask (the fourth mask) is used to define and etch a gate contact opening 2113 in the dielectric layer over the far left gate trench, followed by activation of the implanted dopants. Gate contact opening 2113 provides electrical access to the trenched polysilicon gates which are interconnected along a third dimension not shown in FIG. 19G. In an alternate embodiment, termination p-well 2104A is allowed to float thus eliminating the need for termination source conductor 2121A.

In FIG. 19H, a conductor layer (e.g., comprising metal) is deposited followed by a masking step (fifth) to define and isolate source conductor portions 2121A from gate conductor portion 2121B. As can be seen, only five masks are used in the process depicted by FIGS. 19A-19H. The thin layer directly beneath the gate and source conductor layers is an optional barrier metal.

FIGS. 20A-20G are cross section views of another process sequence using fewer masks as compared to the process depicted by FIGS. 18A-18I. The process steps corresponding to FIGS. 20A-20D are similar to those corresponding to FIGS. 18A-18D, and thus will not be explained. The process sequence corresponding to FIG. 20E is similar to that corresponding to FIG. 18E except that the fourth mask is used to form an additional opening 2217 in the termination dielectric layer over surface polysilicon 2212C. The process sequence corresponding to FIG. 20F is similar to that corresponding to FIG. 18F. However, because of opening 2217 (in FIG. 20E) over surface polysilicon 2212C, the silicon etch for recessing the exposed mesa surfaces also etches the exposed portion of surface polysilicon 2212C creating an opening 2218 therein. Sidewalls of the surface polysilicon thus become exposed through contact opening 2218. Depending on the depth of mesa recess in the active area and the thickness of surface polysilicon 2212C, the mesa recess etch may etch clear through surface polysilicon 2212C or leave a thin layer of polysilicon along the bottom of opening 2218. In one embodiment, opening 2218 is formed such that its aspect ratio allows the two angled source implants 2218 to reach the sidewalls of

surface polysilicon portions 2213A and 2213B. This advantageously minimizes the contact resistance between later formed gate conductor layer 2221B (FIG. 20G) and surface polysilicon portions 2213A and 2213B.

The process sequence corresponding to FIG. 20G is similar to that corresponding to FIG. 18H except that the FIG. 20G process sequence includes activation of the implanted regions. Also, unlike FIG. 18H wherein gate conductor 2021B contacts a top surface of polysilicon 2012C, gate conductor 2221B in FIG. 20G contacts the sidewalls of the surface polysilicon through opening 2218. If after the silicon recess step in FIG. 20F the surface polysilicon 2212C is not fully etched through (i.e., a portion of it remains along the bottom of opening 2218), then gate conductor 2021B would also contact a surface area of the remaining polysilicon in opening 2218.

In FIG. 20G, the thin layer directly beneath the source and gate conductor layers is an optional barrier metal. This embodiment is advantageous in that similar to the FIGS. 19A-19H embodiment only five masks are used up through the step of forming the top-side conductors, and also surface area is preserved by eliminating the need for source conductor layer 2121A (FIG. 19H) surrounding the peripheral gate conductor layer 2121B (FIG. 19H).

FIGS. 21A-21H are cross section views at different processing steps for forming a similar trenched-gate FET to that resulting from the process depicted by FIGS. 18A-18I, except that a Schottky diode is integrated with the FET. The process sequence corresponding to FIG. 21A is similar to that corresponding to FIG. 18A and thus will not be explained. In FIG. 21B, using a p-well blocking mask (the second mask), p-type impurities are implanted and driven in to form well regions 2304 in n-type silicon region 2300. The implanted impurities may alternatively be driven in at a later stage of the process sequence. The p-well blocking mask prevents the p-type impurities from being implanted into a portion 2303 of silicon region 2300 which, as will be seen, forms the Schottky region.

In FIGS. 21C and 21D, similar sets of process steps to those for FIGS. 18C and 18D are carried out and thus will not be described. In FIG. 21E, similar process steps to those for FIG. 18E are carried out however, the contact mask (fifth) and dielectric planarization steps are carried out such that portion 2314D of the insulating layer remains over Schottky region 2303 to prevent this region from receiving dopants during the later source and heavy body implant steps (FIG. 21F). The process sequence corresponding to FIG. 21F is similar to that corresponding to FIG. 18F and thus will not be described.

In FIG. 21G, an implant activation step is carried out to drive in the implanted dopants. A sixth mask is then used to define and etch both the insulating region 2314D from over the Schottky region 2303 and to form gate contact opening 2319 over the surface gate 2312C. The process sequence corresponding to FIG. 21H is the same as that corresponding to FIG. 18H, except that source conductor 2321A, in addition to contacting the source and heavy body regions, contacts Schottky region 2303 to form a Schottky contact with silicon region 2300 using, for example, titanium silicide as a barrier metal. A trenched-gate FET with an integrated Schottky diode is thus formed.

While FIGS. 21A-21H show how a Schottky diode is integrated with the process sequence depicted by FIGS. 18A-18I, the process sequences depicted by each of FIGS. 19A-19H, 20A-20G, 21A-21H, 22A-22F, 23A-23I, and 24A-24I may similarly be modified to integrate a Schottky diode therewith.

FIGS. 22A-22F are cross section views of another process sequence for forming a trenched-gate FET in accordance with an embodiment wherein the number of masks through forma-

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tion of the top-side source and gate conductors is reduced to four. In FIG. 22A, a pad oxide layer (not shown) is formed over n-type silicon region 2400. Dopants of p-type conductivity are implanted and driven in to form p-well region 2404 in n-type silicon region 2400. The implanted impurities may alternatively be driven in at a later stage of the process sequence. A first mask is used to define and etch both trenches 2406 in the active region and wide trench 2401 in the termination region. A LOCOS thick bottom oxide (TBO) process is then used to form a layer of insulating material 2402 along the bottom portion of both the active trenches 2406 and the wide termination trench 2401 trench, as well as over a top surface of the silicon mesa between adjacent trenches.

The process steps corresponding to FIG. 22C are similar to those corresponding to FIG. 20D, however in FIG. 22C instead of forming a planar surface polysilicon 2212C as in FIG. 20D, polysilicon 2412C extends over termination p-well 2204A and down into wide trench 2401. The process steps corresponding to each of FIGS. 22D, 22E, and 22F are similar to those corresponding to each of FIGS. 20E, 20F, and 20G, respectively, and thus will not be described. As can be seen in FIG. 22F, the gate conductor 2421B makes contact to sidewalls of gate 2412D inside the wide trench in the termination region. As in the FIGS. 20A-20G embodiment, if after the silicon recess step in FIG. 22E, the termination polysilicon 2412C is not fully etched through (i.e., a portion of it remains along the bottom of opening 2218 in polysilicon 2412C), then gate conductor 2021B would also contact a surface area of the remaining polysilicon in opening 2218. A total of 4 masks are used, which together with the passivation pad mask (as, for example, identified in the process sequence corresponding to FIG. 18I) makes a total of 5 masks.

FIGS. 23A-23I are cross section views at different processing steps for forming a trench-gate FET with self-aligned features, in accordance with yet another embodiment of the invention. The process steps corresponding to FIGS. 23A-23D are similar to those corresponding to FIGS. 18A-18D, and thus will not be described. In FIG. 23E, a dielectric layer is formed over the structure. A fourth mask is then used to cover the termination region as a dielectric planarization etch is carried out in the active region so that dielectric caps 2514A remain over each trench gate 2512A. In FIG. 23F, a mesa recess etch is carried out to recess the p-type well regions 2504B below the top surface of dielectric caps 2514A such that upper sidewalls of dielectric caps 2514A become exposed. A blanket implant of dopants (e.g., arsenic) is then carried out to form n+ regions 2517 in well regions 2504B between adjacent trenches. Nitride spacers 2518 are then formed over n+ regions 2517 along the exposed sidewalls of dielectric caps 2514A using conventional techniques. In FIG. 23G, the exposed silicon mesa between adjacent spacers 2518 are recessed to a depth within well regions 2504B. The silicon recess removes the middle portion of n+ region 2517 (FIG. 23F), leaving outer portions 2520 of n+ regions 2517 extending directly below spacers 2518 intact. Portions 2520 form the transistor source regions. Dopants of p-type impurity are then implanted to form heavy body regions 2516.

In FIG. 23H, nitride spacers 2518 are removed using conventional techniques. A fifth mask is then used in the termination region to create openings 2515 and 2519 in dielectric region 2514B. In FIG. 23I, source and gate conductors are formed in a similar manner to those in FIG. 18I. A total of six masks are thus used. This process sequence is particularly suitable for forming trench gate FETs with wide pitch body. Also, this process sequence advantageously results in formation of source and heavy body regions which are self-aligned to the trenches.

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FIGS. 24A-24I are cross section views at different processing steps for forming a trench-gate FET in accordance with yet another embodiment of the invention. The process steps corresponding to FIGS. 24A-24D are similar to those corresponding to FIGS. 19A-19D and thus will not be described. In FIG. 24E, a dielectric layer is formed over the structure. A third mask is then used to cover the termination region as a dielectric planarization etch is carried out in the active region so as to form dielectric caps 2614A over each trench gate 2612. The process steps corresponding to FIGS. 24F and 24G are similar to those corresponding to FIGS. 23F and 23G, respectively, and thus will be not described.

In FIG. 24H, nitride spacers 2618 are removed using conventional techniques. A fourth mask is then used in the termination region to create opening 2615 in dielectric region 2614B (FIG. 24G). In FIG. 24I, a metal layer is formed over the structure, and a fifth mask is used to define source conductor 2621A and gate conductor 2621B. As shown, source conductor 2621A contacts heavy body regions 2616 and source regions 2620 along their top surface and sidewall. Termination well region 2604B electrically floats. Alternatively, well region 2604B may be biased via an electrical contact made along the dimension into the page.

Similar to the embodiment represented by FIGS. 23A-23I, this embodiment is suitable for forming trench gate FETs with wide pitch body, and has source and heavy body regions which are self-aligned to the trenches. However, this embodiment advantageously requires one less mask than the FIG. 23A-23I embodiment.

While the various process sequences depicted by FIGS. 18A-18I, 19A-19H, 20A-20G, 21A-21H, 22A-22F, 23A-23I, and 24A-24I are shown in the context of a single gate trench structure, modifying these process sequence to include a shield electrode beneath the gate, similar to shield gate 1324 in FIG. 10, would be obvious to one skilled in this art in view of this disclosure.

The various structures and methods of the present invention may be combined with one or more of a number of charge spreading techniques disclosed in the above-referenced commonly assigned application Ser. No. 11/026,276, to achieve even a lower on-resistance, higher blocking capability and higher efficiency.

The cross-section views of the different embodiments may not be to scale, and as such are not intended to limit the possible variations in the layout design of the corresponding structures. Also, the various transistors can be formed in open cell architecture (e.g., stripe) or closed cell architecture (e.g., hexagonal or square shaped cells).

Although a number of specific embodiments are shown and described above, embodiments of the invention are not limited thereto. For example, it is understood that the doping polarities of the structures shown and described could be reversed and/or the doping concentrations of the various elements could be altered without departing from the invention. As another example, various exemplary accumulation-mode and enhancement mode vertical transistors described above have the trenches terminating in the drift region (a lightly doped epitaxial layer extending over the substrate), but they can also terminate in the more heavily doped substrate. Also, the features of one or more embodiments of the invention may be combined with one or more features of other embodiments of the invention without departing from the scope of the invention. For this and other reasons, therefore, the above description should not be taken as limiting the scope of the invention, which is defined by the appended claims.

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What is claimed is:

1. A method of forming a field effect transistor comprising an active area and a termination region surrounding the active area, the method comprising:

forming gate trenches extending into a silicon region of a first conductivity type;

forming a well region of a second conductivity type in the silicon region;

forming a recessed gate in each gate trench;

forming a dielectric cap over each gate;

recessing all exposed surfaces of the well region to form a recess in the well region between every two adjacent trenches such that the recess has sloped walls and a bottom located between a top surface of the dielectric cap and a top surface of the recessed gate; and

without masking any portion of the active area, performing a zero-degree blanket implant to form a heavy body region of the second conductivity type in the well region between every two adjacent trenches whereby the heavy body region is self-aligned to the gate trenches.

2. The method of claim 1 further comprising performing a two-pass angled implant into the sloped walls of each recess to thereby form source regions of the first conductivity type adjacent the dielectric cap, the sloped walls of the recess forming an outer wall of each source region, the source regions being self-aligned to the trenches.

3. The method of claim 2 further comprising forming a source conductor contacting the outer wall of each source region and contacting the heavy body region along the bottom of the recess.

4. The method of claim 1 further comprising:

forming a wide trench in the termination region; and

filling the wide trench with LOCOS.

5. The method of claim 1 further comprising forming a surface gate in the termination region simultaneously with forming the recessed gate in the gate trenches.

6. The method of claim 5 further comprising:

forming an opening over the surface gate; and

forming a gate conductor contacting the surface gate through the opening.

7. The method of claim 1 further comprising:

forming a termination trench in the termination region simultaneously with forming the gate trenches;

forming a recessed gate in the termination trench simultaneously with forming the recessed gate in the gate trenches;

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forming an opening over the recessed gate in the termination trench; and

forming a gate conductor contacting the recessed gate in the termination trench through the opening.

8. The method of claim 5 further comprising:

forming an opening over the surface gate; and

simultaneously with recessing all exposed surfaces of the well region, recessing the surface gate through the opening to thereby expose sidewalls of the surface gate through the opening; and

filling the opening with a gate conductor, the gate conductor contacting the surface gate along the exposed sidewalls of the surface gate.

9. The method of claim 1 further comprising:

simultaneously with forming the gate trenches, forming a wide trench in the termination region; and

filling a bottom portion of the wide trench and each gate trench with LOCOS.

10. The method of claim 9 further comprising forming a termination gate simultaneously with forming the recessed gate in the gate trenches, the termination gate extending in part inside the wide trench and in part over a mesa region adjacent the wide trench.

11. The method of claim 10 further comprising:

forming a contact opening over the termination gate in the wide trench; and

simultaneously with recessing all exposed surfaces of the well region, recessing the termination gate through the opening to thereby expose sidewalls of the termination gate through the opening; and

filling the opening with a gate conductor, the gate conductor contacting the exposed sidewalls of the termination gate.

12. The method of claim 1 further comprising:

prior to forming the recessed gate, forming a thick bottom dielectric along a bottom portion of each gate trench; and

prior to forming the recessed gate, forming a gate dielectric lining the sidewalls of each gate trench, wherein the thick bottom dielectric is thicker than the gate dielectric.

13. The method of claim 1 further comprising:

prior to forming the recessed gate, forming a shield electrode along a bottom portion of each gate trench; and

prior to forming the recessed gate, forming a dielectric layer over each shield electrode.

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