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(54) **DIODES WITH SCHOTTKY CONTACT INCLUDING LOCALIZED SURFACE REGIONS**

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H10D 62/10	(2025.01)
H10D 62/832	(2025.01)

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CPC ***H10D 8/60*** (2025.01); ***H10D 62/109*** (2025.01); ***H10D 62/8325*** (2025.01)

(58) **Field of Classification Search**
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(Continued)

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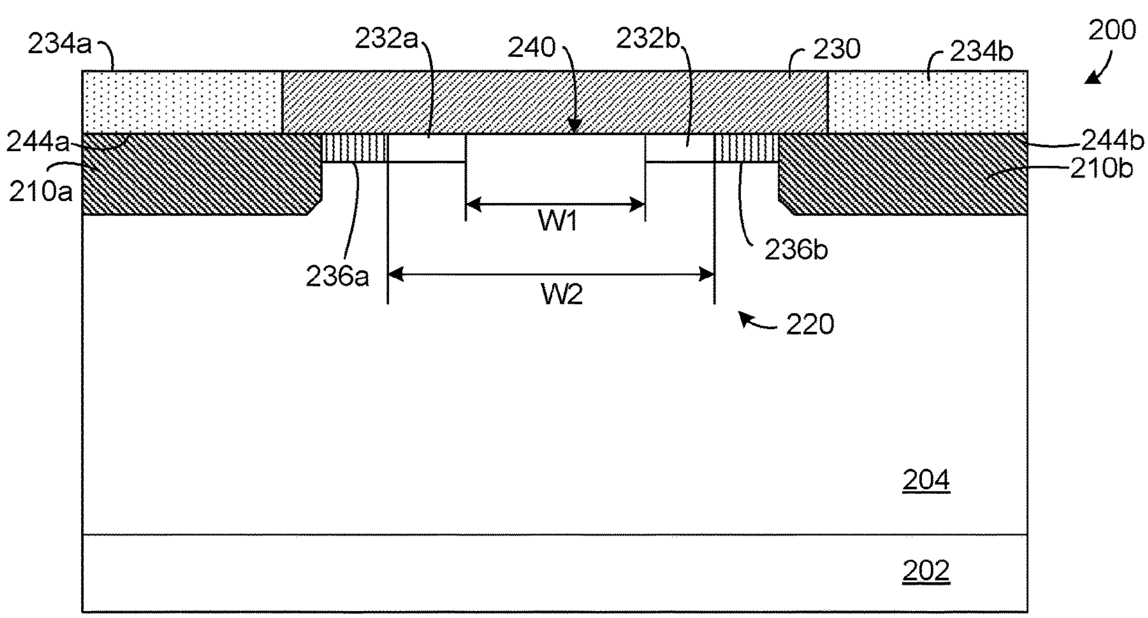
(57) **ABSTRACT**

In some aspects, the techniques described herein relate to a diode including: a substrate of a first conductivity type; a semiconductor layer of the first conductivity type disposed on the substrate, the semiconductor layer including a drift region; a shield region of a second conductivity type disposed in the semiconductor layer adjacent to the drift region; a surface region of the first conductivity type disposed in a first portion of the drift region adjacent to the shield region, the surface region having a doping concentration that is greater than a doping concentration of a second portion of the drift region adjacent to the surface region, the second portion of the drift region excluding the surface region; and a Schottky material disposed on: at least a portion of the shield region; the surface region in the first portion of the drift region; and the second portion of the drift region.

20 Claims, 7 Drawing Sheets



(58) **Field of Classification Search**
USPC 257/409
See application file for complete search history.

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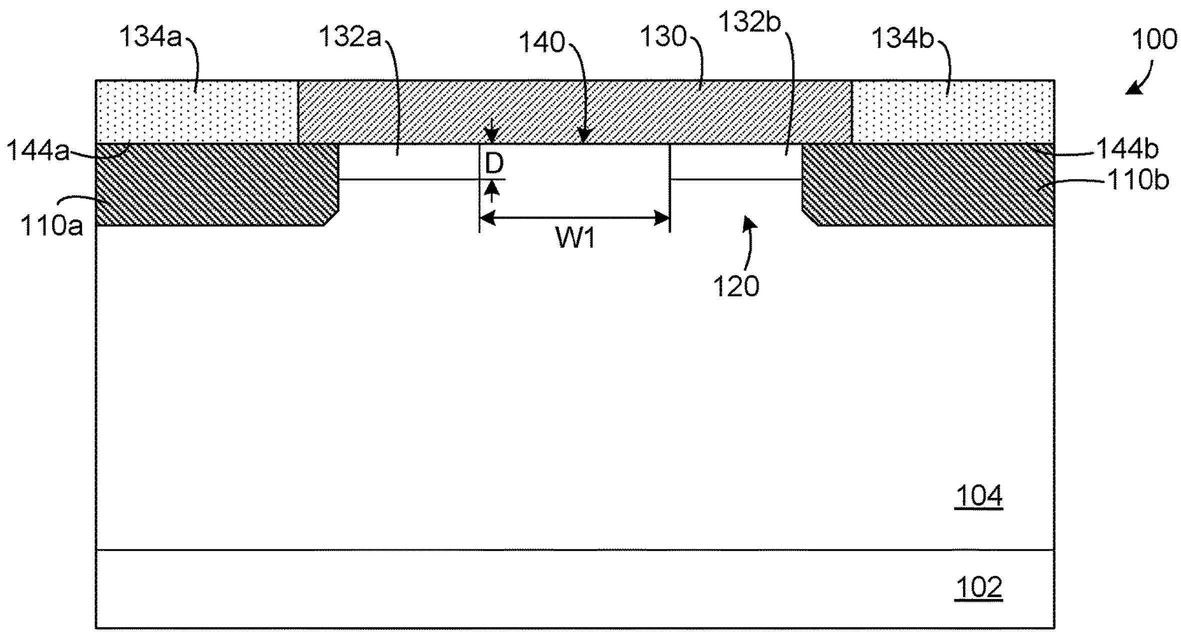
134a
132a
140
130
132b
134b
100
144a
D
144b
110b
110a
W1
120
104
102

FIG. 1

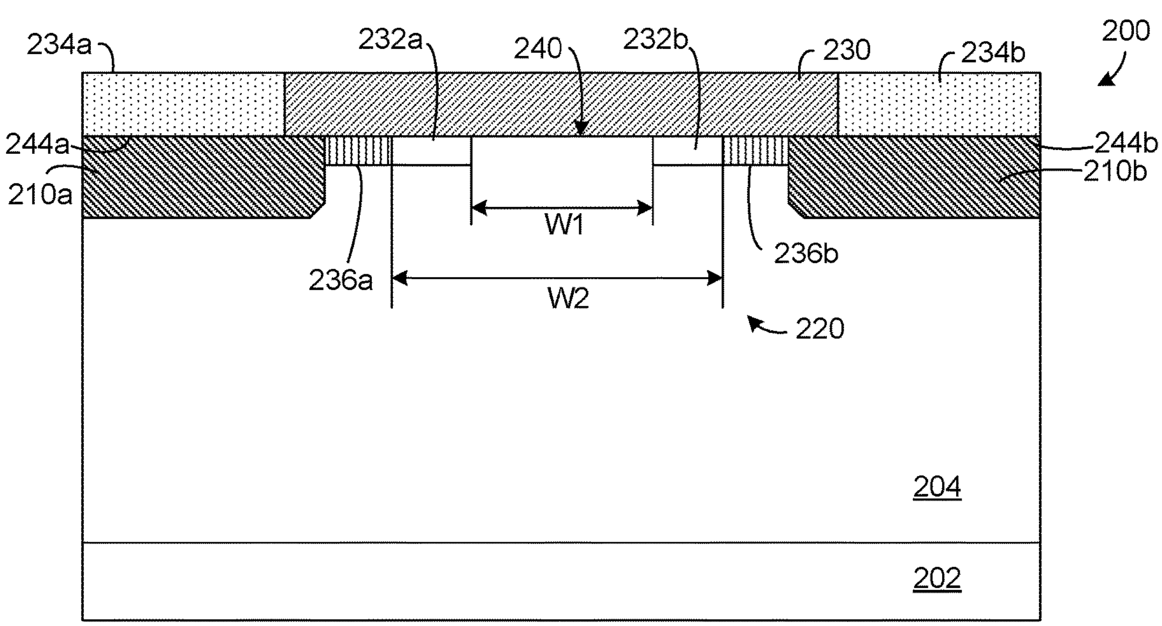
234a
232a
240
232b
230
234b
200
244a
244b
210a
210b
W1
236b
236a
W2
220
204
202

FIG.2

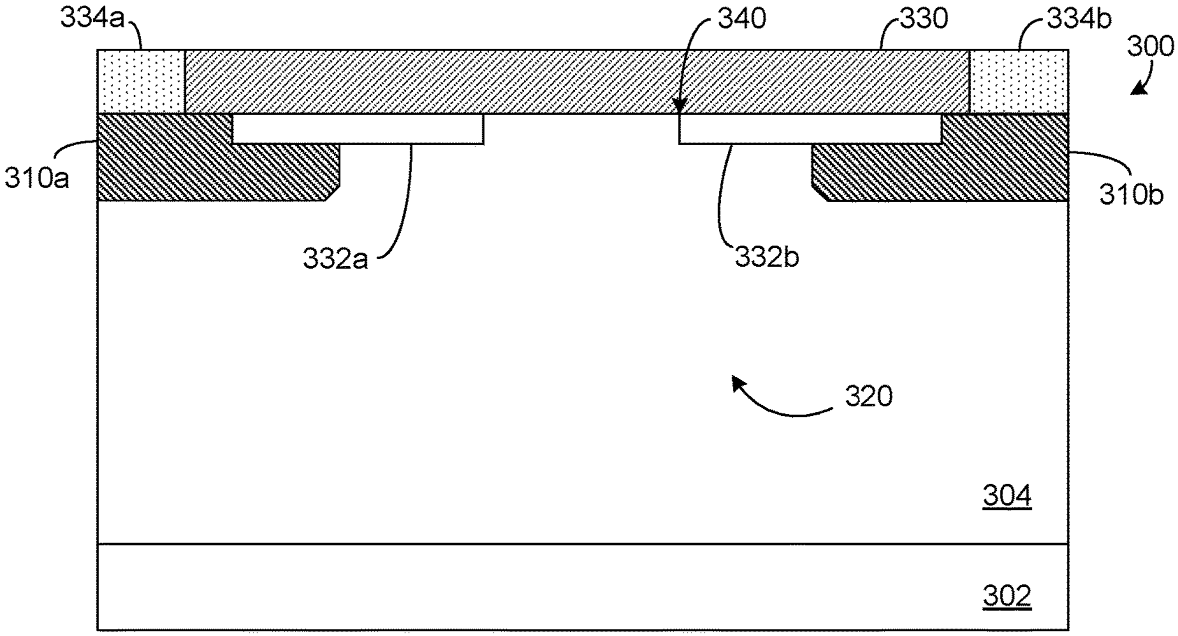
334a
340
330
334b
300
310a
310b
332a
332b
320
304
302

FIG. 3

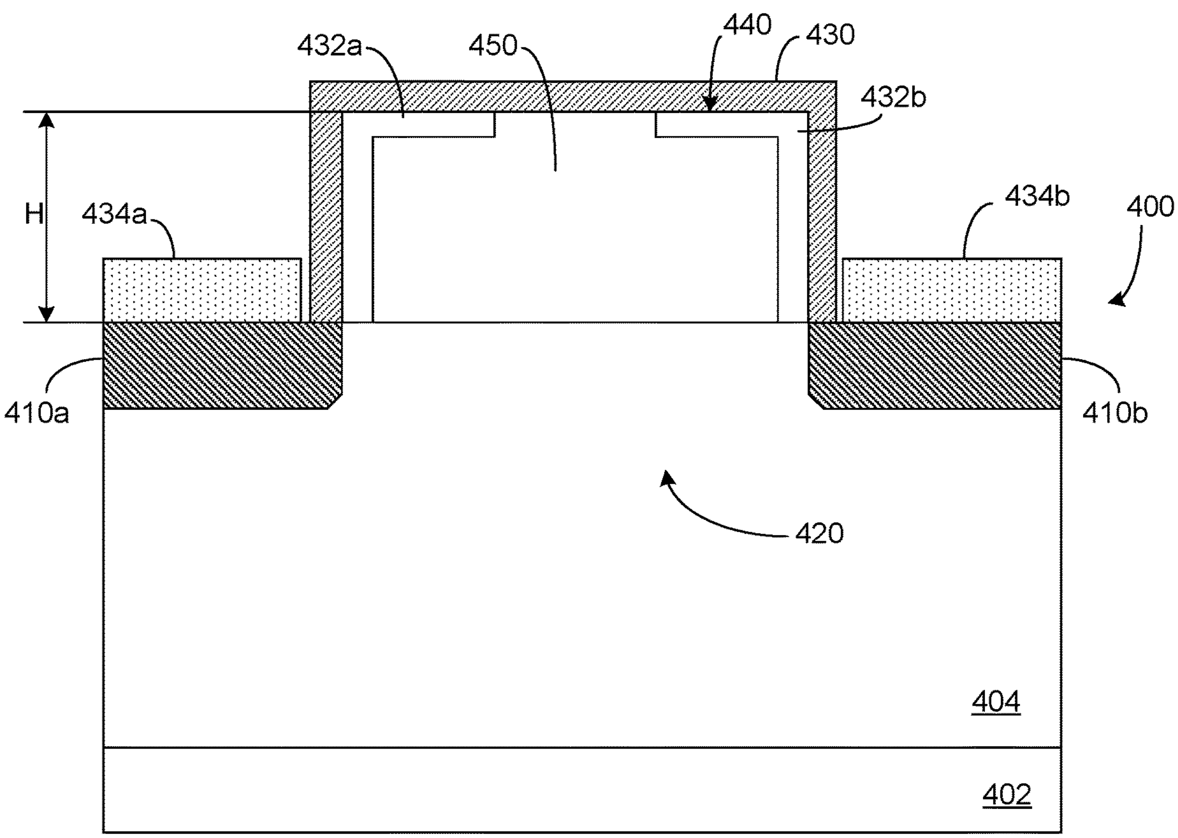
432a
450
440
430
432b
H
434a
434b
400
410a
410b
420
404
402

FIG. 4

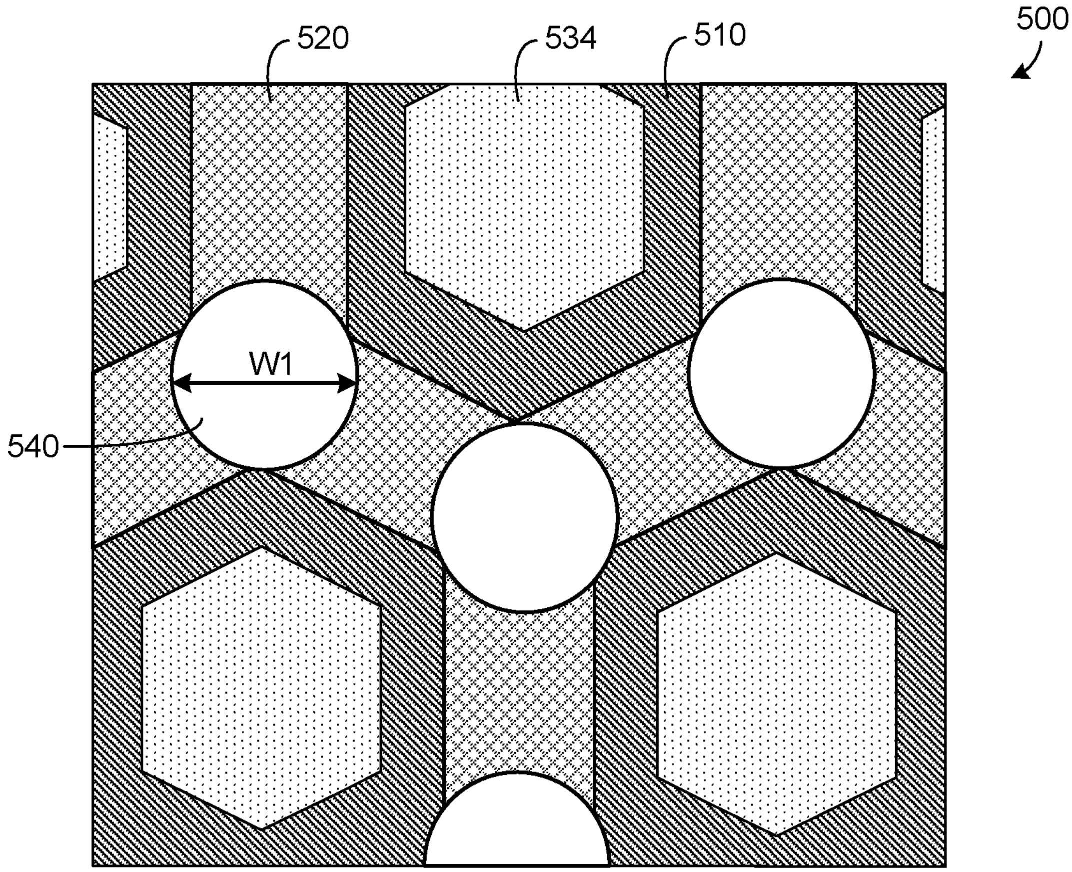

FIG. 5

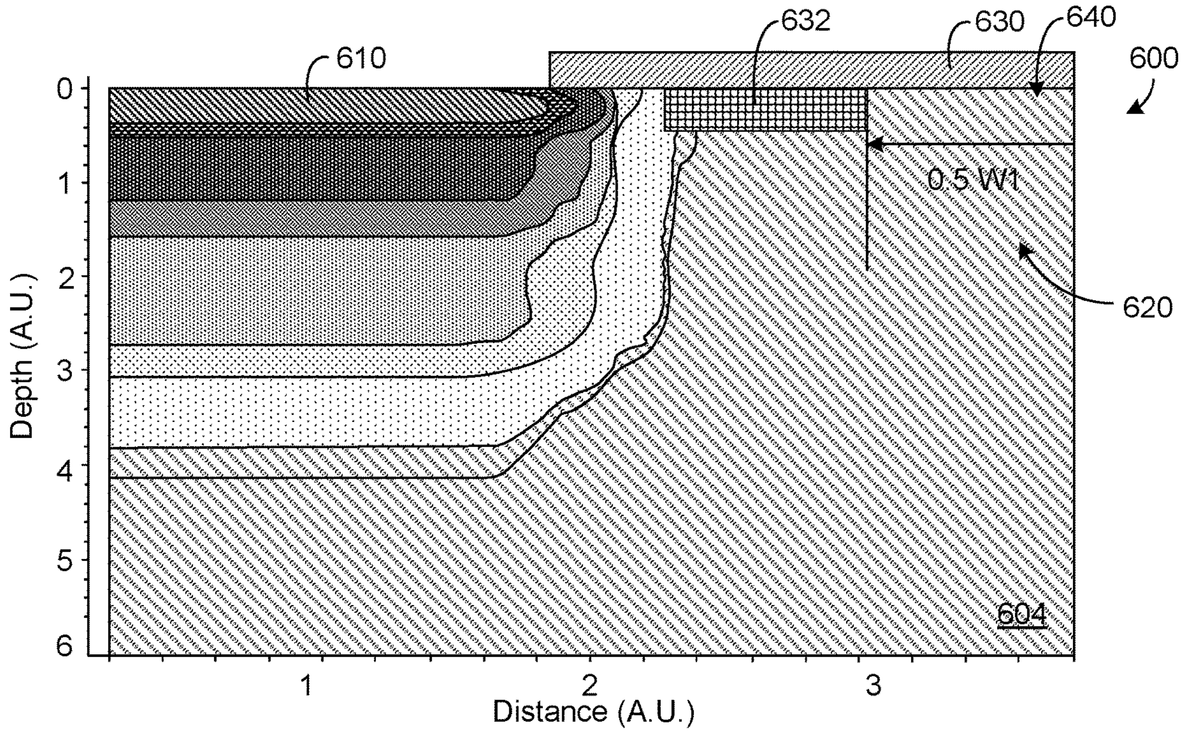
610
632
630
640
600
0.5 W1
620
604
Depth (A.U.)
0
1
2
3
4
5
6
1
2
3
Distance (A.U.)

FIG. 6

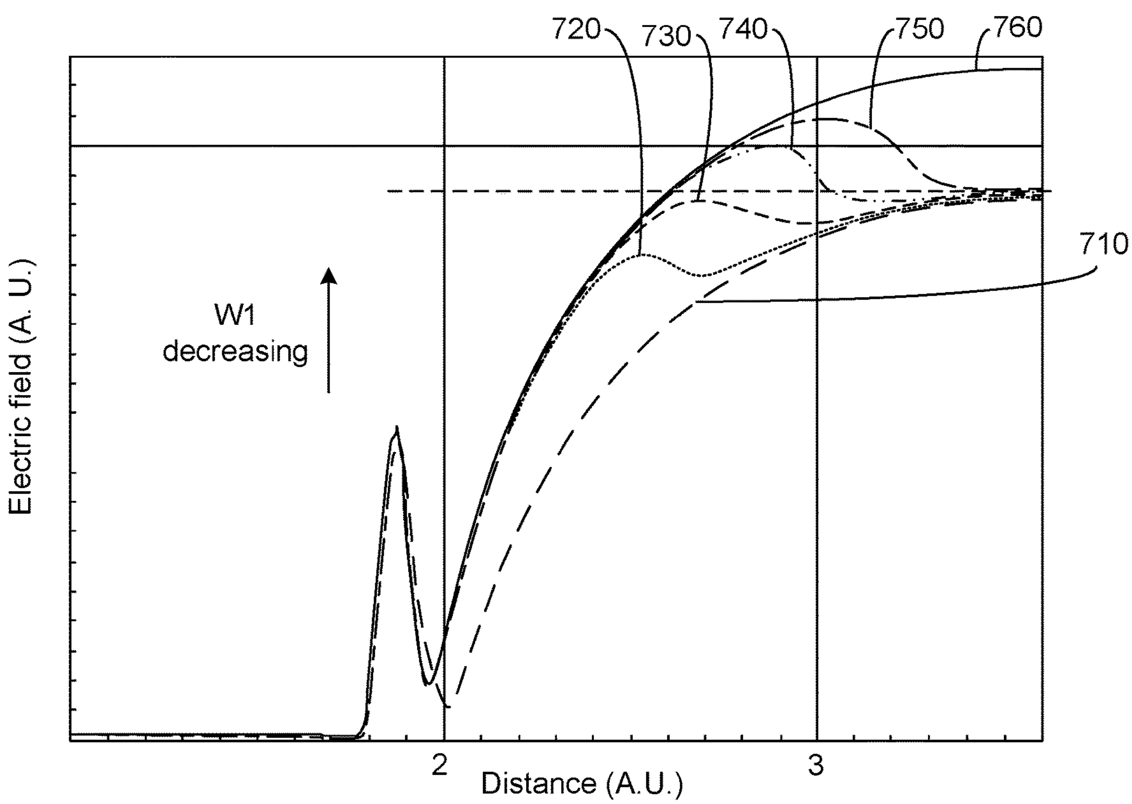
720
730
740
750
760
710
W1
decreasing
Electric field (A. U.)
2
3
Distance (A.U.)

FIG. 7

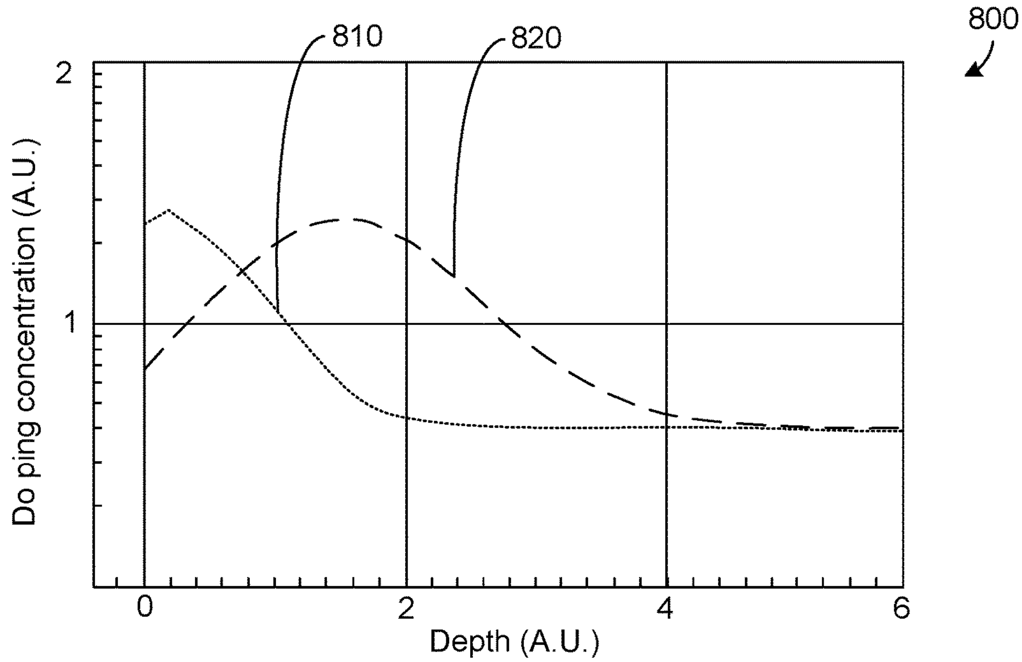
800
810
820
Do ping concentration (A.U.)
Depth (A.U.)
2
1
0
2
4
6

FIG. 8

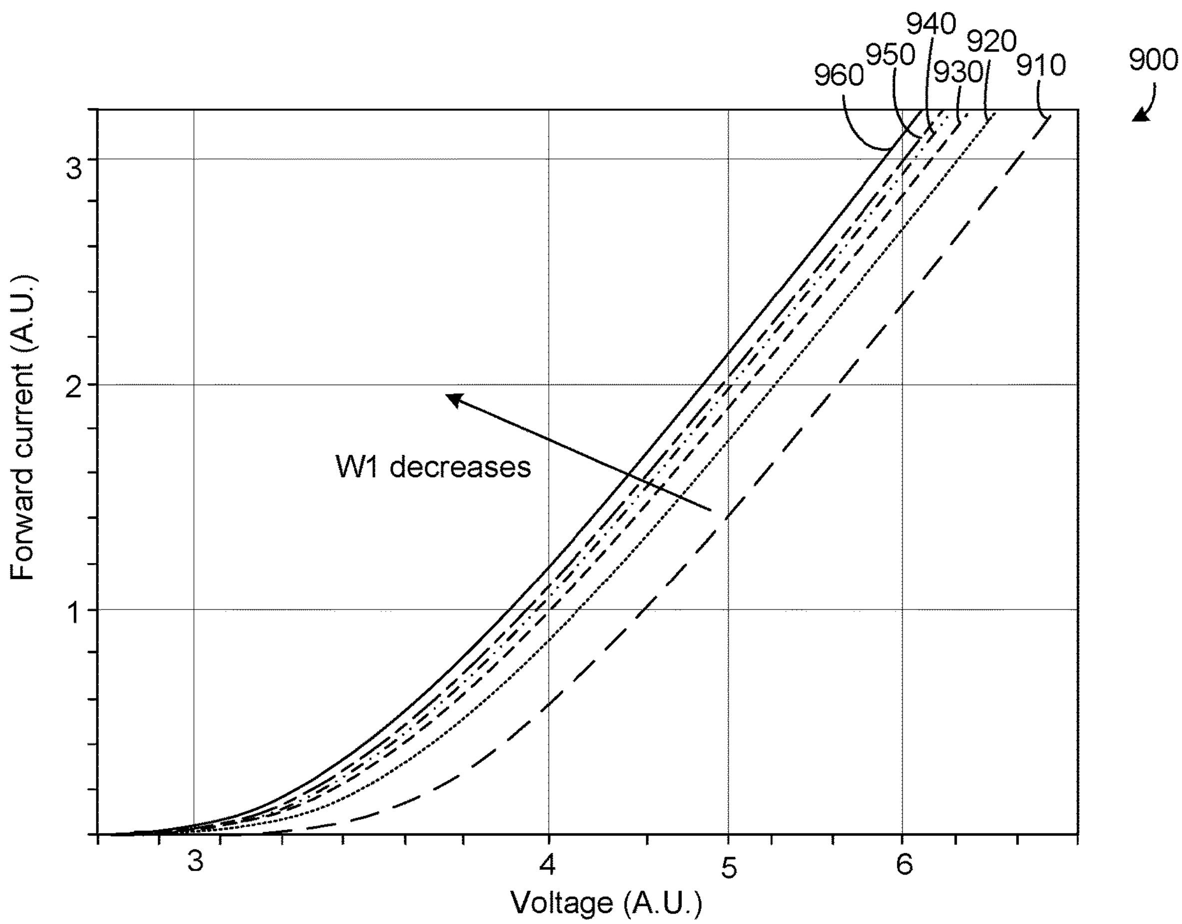
900
960
950
940
930
920
910
W1 decreases
Forward current (A.U.)
Voltage (A.U.)
3
2
1
3
4
5
6

FIG. 9

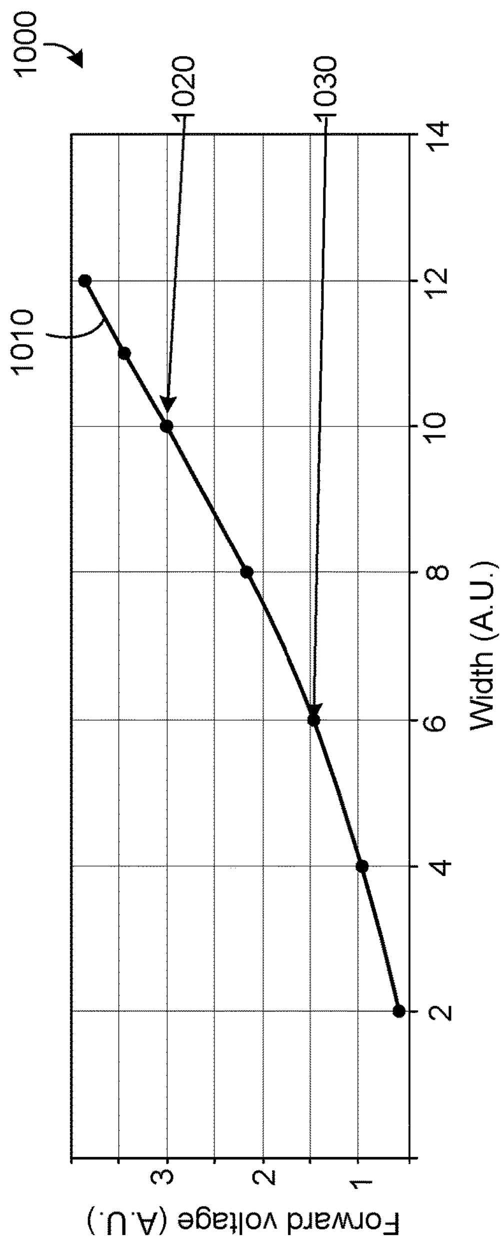

FIG. 10

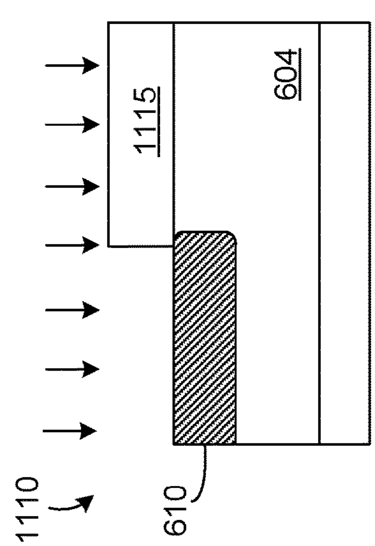

FIG. 11A

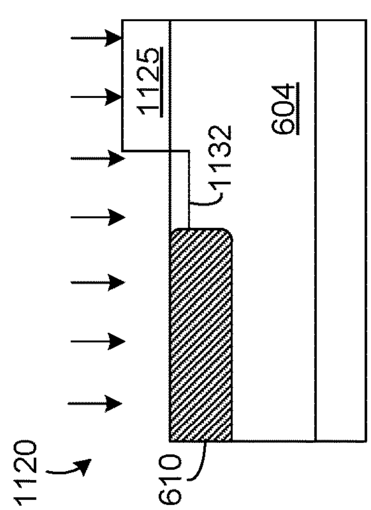

FIG. 11B

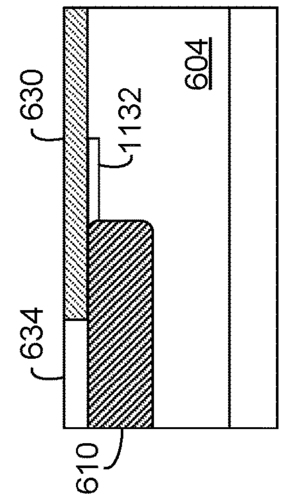

FIG. 11C

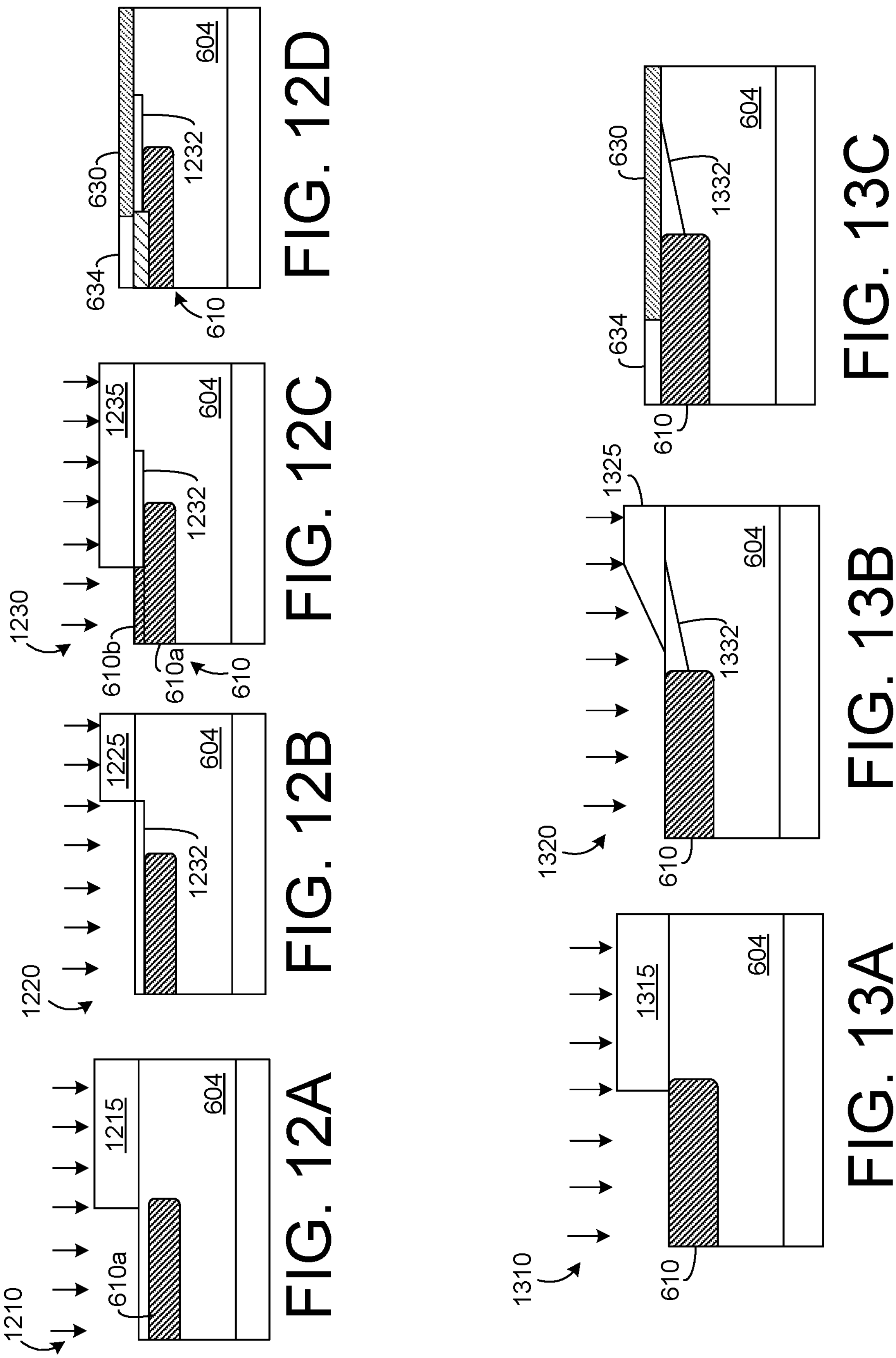

FIG. 12A

FIG. 12B

FIG. 12C

FIG. 12D

FIG. 13A

FIG. 13B

FIG. 13C

DIODES WITH SCHOTTKY CONTACT INCLUDING LOCALIZED SURFACE REGIONS

TECHNICAL FIELD

This description relates to Schottky diodes that include shallow regions to locally modify barrier height and electric field, such as under a Schottky contact in the diode's drift region, to improve the diode's operating characteristics.

BACKGROUND

Semiconductor materials, e.g., silicon (Si) silicon carbide (SiC), gallium nitride (GaN), etc., used to produce high-power semiconductor devices are subject to the presence of high electric fields during operation of associated semiconductor devices, which can operate at 400 volts (V), 600 V, 1200 V, or higher. Schottky diodes utilizing such a power semiconductor materials (e.g., SiC), due to such high electric fields under reverse-biased conditions, can experience leakage currents that approach, or exceed acceptable operating limits. This is due, in part, to the fact that there is a tradeoff between forward-operating characteristics of a Schottky diode, and its reverse-bias leakage current. That is, improving forward-operating characteristics of a Schottky diode, such as reducing conduction losses by reducing forward voltage drop (V_f), results in an increase in leakage current of the diode. Accordingly, in current approaches, in order to reduce on-state conduction losses (e.g., reduce V_f), designers must sacrifice a diode's reverse characteristics, which can result in leakage currents exceeding acceptable values. Conversely in previous approaches, in order to improve a diode's reverse characteristic (e.g., reduce leakage), designers must sacrifice a diode's forward operating characteristics.

SUMMARY

In some aspects, the techniques described herein relate to a diode including: a substrate of a first conductivity type; a semiconductor layer of the first conductivity type disposed on the substrate, the semiconductor layer including a drift region of the diode; a shield region of a second conductivity type disposed in the semiconductor layer adjacent to the drift region; a surface region of the first conductivity type disposed in a first portion of the drift region adjacent to the shield region, the surface region having a doping concentration that is greater than a doping concentration of a second portion of the drift region adjacent to the surface region, the second portion of the drift region excluding the surface region; and a Schottky material disposed on: at least a portion of the shield region; the surface region in the first portion of the drift region; and the second portion of the drift region.

In some aspects, the techniques described herein relate to a diode, wherein the surface region is disposed between the shield region and the second portion of the drift region.

In some aspects, the techniques described herein relate to a diode, wherein the surface region is a first surface region, the diode further including: a second surface region of the first conductivity type disposed in a third portion of the drift region, the second surface region being disposed adjacent to the first surface region, the second surface region having a doping concentration that is greater than the doping concentration of the second portion of the drift region and less

than the doping concentration of the first surface region, the Schottky material being further disposed on the second surface region.

In some aspects, the techniques described herein relate to a diode, wherein the second surface region is further disposed between the first surface region and the second portion of the drift region.

In some aspects, the techniques described herein relate to a diode, wherein: the semiconductor layer includes a mesa having a height, the mesa being defined by trenches formed in the semiconductor layer; the surface region being disposed in an upper portion of the mesa; and the Schottky material being disposed on the mesa.

In some aspects, the techniques described herein relate to a diode, wherein the surface region is further disposed in a sidewall of the mesa.

In some aspects, the techniques described herein relate to a diode, wherein: the diode includes an arrangement of geometrically shaped cells; a widest portion of the drift region excludes the surface region; and a narrowest portion of the drift region includes the surface region.

In some aspects, the techniques described herein relate to a diode, wherein: the first conductivity type is n-type; and the second conductivity type is p-type.

In some aspects, the techniques described herein relate to a diode, wherein: the substrate is a silicon carbide substrate; and the semiconductor layer is an epitaxial silicon carbide layer, the substrate having a doping concentration that is higher than a doping concentration of the epitaxial silicon carbide layer.

In some aspects, the techniques described herein relate to a diode, wherein the semiconductor layer includes: a first epitaxial semiconductor layer of the first conductivity type, the first epitaxial semiconductor layer being disposed on the substrate; and a second epitaxial semiconductor layer of the first conductivity type, the second epitaxial semiconductor layer being disposed on the first epitaxial semiconductor layer, the first epitaxial semiconductor layer having a doping concentration that is greater than a doping concentration of the second epitaxial semiconductor layer.

In some aspects, the techniques described herein relate to a diode, wherein the at least a portion of the shield region is a first portion of the shield region, the diode further including: a metal disposed on a second portion of the shield region and defining an ohmic contact to the shield region.

In some aspects, the techniques described herein relate to a diode, wherein the metal disposed on the second portion of the shield region includes at least one of: the Schottky material; a metal silicide; or a deposited metal.

In some aspects, the techniques described herein relate to a diode, wherein the surface region has a depth in the semiconductor layer of 100 nanometers (nm) or less.

In some aspects, the techniques described herein relate to a diode, wherein the surface region is disposed in ten percent to ninety percent of an area of an upper portion of the drift region.

In some aspects, the techniques described herein relate to a diode, wherein the doping concentration of the surface region varies along at least one of: a surface of the semiconductor layer; or a depth of the surface region in the semiconductor layer.

In some aspects, the techniques described herein relate to a diode, wherein the surface region is further disposed in ten percent to ninety percent of an area of an upper portion of the shield region.

In some aspects, the techniques described herein relate to a diode including: a substrate of a first conductivity type; a semiconductor layer of the first conductivity type disposed on the substrate, the semiconductor layer including a drift region of the diode; a first shield region of a second conductivity type disposed in the semiconductor layer adjacent to the drift region; a second shield region of the second conductivity type disposed in the semiconductor layer adjacent to the drift region, the drift region being disposed, at least in part between the first shield region and the second shield region; a surface region of the first conductivity type disposed in a first portion of the drift region between the first shield region and the second shield region, the surface region having a doping concentration that is greater than a doping concentration of a second portion of the drift region adjacent to the surface region, a second portion of the drift region excluding the surface region; and a Schottky material disposed on: at least a portion of the first shield region; at least a portion of the second shield region; the surface region in the first portion of the drift region; and the second portion of the drift region.

In some aspects, the techniques described herein relate to a diode, wherein the surface region is further disposed: between the first shield region and the second portion of the drift region; and between the second shield region and the second portion of the drift region.

In some aspects, the techniques described herein relate to a diode, wherein the surface region is a first surface region, the diode further including: a second surface region of the first conductivity type disposed in a third portion of the drift region, the second surface region including: a first portion disposed between the first shield region and a first portion of the first surface region; and a second portion disposed between the second shield region and a second portion of the first surface region, the second surface region having a doping concentration that is greater than the doping concentration of the second portion of the drift region and less than the doping concentration of the first surface region, the Schottky material being further disposed on the second surface region.

In some aspects, the techniques described herein relate to a diode, wherein the second portion of the drift region is disposed between the first portion of the first surface region and the second portion of the first surface region.

In some aspects, the techniques described herein relate to a method for forming a diode, the method including: forming a semiconductor layer of a first conductivity type disposed on a substrate of the first conductivity type, the semiconductor layer including a drift region of the diode; forming a shield region of a second conductivity type in the semiconductor layer adjacent to the drift region; forming a surface region of the first conductivity type in a first portion of the drift region adjacent to the shield region, the surface region having a doping concentration that is greater than a doping concentration of a second portion of the drift region adjacent to the surface region, the second portion of the drift region excluding the surface region; and depositing a Schottky material disposed on: at least a portion of the shield region; the surface region in the first portion of the drift region; and the second portion of the drift region.

In some aspects, the techniques described herein relate to a method, wherein the doping concentration of the surface region varies along at least one of: a surface of the semiconductor layer; or a depth of the surface region in the semiconductor layer.

In some aspects, the techniques described herein relate to a method, wherein the surface region is a first surface region, the method further including: forming a second surface region of the first conductivity type in a third portion of the drift region, the second surface region being disposed adjacent to the first surface region, the second surface region having a doping concentration that is greater than the doping concentration of the second portion of the drift region and less than the doping concentration of the first surface region, the Schottky material being further disposed on the second surface region.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a diagram illustrating a cross-sectional view of a Schottky diode including localized surface regions, according to an implementation.

FIG. **2** is a diagram illustrating a cross-sectional view of another Schottky diode including localized surface regions, according to an implementation.

FIG. **3** is a diagram illustrating a cross-sectional view of yet another Schottky diode including localized surface regions, according to an implementation.

FIG. **4** is a diagram illustrating a cross-sectional view of still another Schottky diode implemented in a semiconductor mesa including localized surface regions, according to an implementation.

FIG. **5** is a diagram illustrating a top-down (plan) view of still another Schottky diode including localized surface regions, according to an implementation.

FIG. **6** is a diagram illustrating a cross-sectional view of a half-cell of a Schottky diode (e.g., half a diode cell) including a localized drift region implant, such as the diode of FIG. **1**.

FIG. **7** is a graph illustrating electric fields of various implementations of the diode of FIG. **6** (or FIG. **1**) under reverse-bias condition.

FIG. **8** is a graph illustrating an example of doping concentration of localized surface regions.

FIG. **9** is graph illustrating forward IV characteristics for implementations of the diode of FIG. **1** compared to a prior diode implementation.

FIG. **10** is a graph illustrating forward voltage drop for the diode implementations illustrated in FIG. **9**.

FIG. **11**A-**11**C are diagrams illustrating cross-sectional views of an example method for forming localized surface regions in a Schottky diode.

FIG. **12**A-**12**D are diagrams illustrating cross-sectional views of another example method for forming localized surface regions in a Schottky diode.

FIG. **13**A-**13**C are diagrams illustrating cross-sectional views of yet another example method for forming localized surface regions in a Schottky diode.

In the drawings, which are not necessarily drawn to scale, like reference symbols may indicate like and/or similar components (elements, structures, etc.) in different views. The drawings illustrate generally, by way of example, but not by way of limitation, various implementations discussed in the present disclosure. Reference symbols show in one drawing may not be repeated for the same, and/or similar elements in related views. Reference symbols that are repeated in multiple drawings may not be specifically discussed with respect to each of those drawings, but are provided for context between related views. Also, not all like elements in the drawings are specifically referenced with a reference symbol when multiple instances of that element are illustrated.

DETAILED DESCRIPTION

The present disclosure is directed to diodes with Schottky contacts (e.g., Schottky diodes), and associated methods of producing such diodes. In the approaches described herein, localized surface regions (e.g., surface regions with a depth of 100 nanometers or less) are used to locally alter areas of a Schottky interface in an underlying semiconductor material (e.g., in an upper portion of a drift region of the diode). That is, such surface regions can be included in a Schottky interface (e.g., Schottky contact) of a diode to locally alter barrier height, and associated electric field of the Schottky interface. In some implementations, such surface regions can be formed by ion implantation, in situ doping, or by using other approaches. By locating the surface regions in portions of the Schottky contact of the diode with lower electric fields, an effective turn-on voltage, or forward voltage drop V_f, (thus on-state losses) of the diode can be reduced without significantly impacting reverse blocking capabilities of the diode (e.g., without significantly increasing reverse-biased leakage current). In some implementations, both forward and reverse operating characteristics of a Schottky diode can be improved.

FIG. **1** is a diagram illustrating a cross-sectional view of a Schottky diode **100** (diode) including surface regions (e.g., formed by localized surface implants), according to an implementation. In some implementations, the diode **100** can have a linear (striped) cell layout, (e.g., having identical structure and dimensions into and/or out of the page). In some implementations, the diode **100** can have a cellular layout, such as the example shown in FIG. **5**. The diode **100** illustrates a cross-sectional view of a single diode cell perpendicular to the stripe of the linear cell layout, which can be interconnected with other diode stripes or diode cells to form a larger diode (e.g., by electrically connecting the respective anodes together and by electrically connecting the respective cathodes together). Depending on the particular implementation, the spacing, sizing and arrangement of the elements of the diode **100** can be different.

As shown in FIG. **1**, the diode **100** includes a substrate **102** and a semiconductor layer **104** (semiconductor region). The substrate **102** and the semiconductor layer **104** can be of a first conductivity type, e.g., n-type conductivity. The substrate **102** can have a doping concentration that is higher than a doping concentration of the semiconductor layer **104**. In some implementations, the semiconductor layer **104** can be an epitaxial semiconductor layer, or can include multiple epitaxial semiconductor layers with different doping concentrations. That is, in the view of FIG. **1**, the upper portion of the semiconductor layer **104** can have a doping concentration that is higher than a doping concentration of the lower portion of the semiconductor layer **104**, or can gradually increase along a depth of the semiconductor layer **104**, e.g., depth from an upper surface of the semiconductor layer **104** to a bottom of the semiconductor layer **104**. In some implementations, the substrate **102** and the semiconductor layer **104** can include silicon carbide, or other semiconductor materials. In some implementations, n-type doping can be provided by incorporation of nitrogen, phosphorous, etc.

The diode **100** includes a shield region **110***a* and a shield region **110***b* that are disposed in the semiconductor layer **104**. The shield region **110***a* and the shield region **110***b* are disposed adjacent to a drift region **120** of the diode **100**. The shield region **110***a* and the shield region **110***b* of the diode **100** are of a second conductivity type that is opposite the first conductivity type, e.g., p-type conductivity. In some implementations, the first and second conductivity types can be reversed. In some implementations, p-type doping can be provided by incorporation of aluminum, boron, etc.

The diode **100** also includes a Schottky material **130** that defines a Schottky contact **140** with the drift region **120**, e.g., along a surface of the drift region **120** between the shield region **110***a* and the shield region **110***b*. In example implementations, the Schottky material **130** can include a metal, an alloy, a semiconductor material, and/or other material that defines a Schottky barrier with the drift region **120**. The drift region **120** includes a surface region **132***a* and a surface region **132***b* that are disposed in respective first and second upper portions of the drift region **120**, and are included in an interface (Schottky interface) of the Schottky contact **140**. As shown in FIG. **1**, the surface regions **132***a* and **132***b*, as well as the other surface regions described herein, can have a depth D. In some implementations, the depth D, as indicated above, can be on the order of 100 nanometers, or less.

The surface regions **132***a* and **132***b*, in this example, are of the first conductivity type, and can be formed simultaneously (e.g. using a same implantation process). As shown in FIG. **1**, a central (third) upper portion of the drift region **120** along the interface of the Schottky contact **140** excludes a surface region. In this example, the surface regions **132***a* and **132***b* have a higher doping concentration than portions of the drift region **120** excluding such implants, such as the central portion.

As shown in FIG. **1**, with respect to the interface of the Schottky contact **140**, the surface regions **132***a* **132***b* are disposed in an respective upper portions (e.g., first and second portions, respectively) of the drift region **120** adjacent to (and in contact with) the shield regions **110***a* and **110***b*. A third, central, upper portion of the drift region **120**, disposed between the surface regions **132***a* and **132***b*, excludes a localized surface implant, e.g., can have the original doping concentration of the semiconductor layer **104**.

The surface regions **132***a* and **132***b*, in this example, locally alter (lower) a barrier height of the Schottky contact **140**, as well as locally alter (increase) associated electric fields in the portions of the drift region **120** including the surface regions **132***a* and **132***b* during reverse bias operation. Accordingly, in this example, the Schottky contact **140** corresponding with the central portion of the drift region **120** will have a barrier height that is greater than a barrier height of the respective portions of the Schottky contact **140** corresponding with the surface regions **132***a* and **132***b*.

As shown in FIG. **1**, the portion of the drift region **120** excluding a surface region (e.g., implant) can have a width W1. In some implementations, the width W1 can be ten percent to ninety percent of a width of the upper portion of the drift region **120** disposed between shield regions **110***a*, **110***b*. In other words, the surface regions **132***a* and **132***b* can occupy ninety percent to ten percent of the upper portion of the drift region **120**. In example implementations, the width W1 can be selected based on electric field distribution at a surface of the drift region **120** (e.g., electric field distribution along the Schottky contact **140** under reverse-bias conditions) to achieve a desired relationship between on-state and off-state operating characteristic of the diode **100**. In the following discussion, references to electric field electric field and electric field distribution refer, respectively, to electric field and electric field distribution under reverse-bias conditions, unless otherwise indicated.

In this example, as W1 is varied (widened or narrowed), an associated surface area of the drift region **120** excluding surface regions on which the Schottky material **130** is disposed will vary (will respectively increase or decrease). Likewise, as W1 is varied, respective surface areas of the surface regions **132***a* and **132***b* on which the Schottky material **130** is disposed will also correspondingly vary. That is, increasing W1 will reduce the respective surface areas of the surface regions **132**a and **132**b included in the Schottky contact **140**, while decreasing W1 will increase the respective surface areas of the surface regions **132**a and **132**b included in the Schottky contact **140**.

In the diode **100**, in the absence of surface regions **132**a **132**b, electric field distribution in the drift region **120** (e.g., just below, for instance, 5 nanometers or less below, the Schottky contact **140**) will be highest at a mid-point between the shield region **110**a and the shield region **110**b, and will decrease moving away from the mid-point, respectively, toward the shield region **110**a and the shield region **110**b (e.g., with a bell-shaped curve distribution). Accordingly, if properly designed, the central portion of the drift region **120** excluding surface regions will have the highest electric field for the diode **100**, while the surface regions **132**a and **132**b are disposed in portions of the drift region **120** with originally lower electric field.

In this example, the portion of the Schottky contact **140** corresponding with the portion of the drift region excluding surface regions will have a higher barrier height than a barrier height of the portions of the Schottky contact **140** corresponding with the surface regions **132**a and **132**b. Accordingly, tradeoff between forward operating characteristics and reverse operating characteristics of the diode **100** can be improved, e.g., as compared to having a uniformly doped surface of the drift region **120** under the Schottky contact **140**.

For instance, in some implementations, the diode **100**, the width W1 and doping of the surface regions **132**a and **132**b can be configured such that respective leakage current density (e.g., total leakage through a specific device portion divided by the area of that portion) and/or respective on-state current densities of the portion of the Schottky contact **140** corresponding to the central portion of the drift region, and the portions of the Schottky contacts **140** corresponding with the surface regions **132**a and **132**b are the same, or substantially the same (e.g., have a same design target). In other implementations the width W1 and the doping of surface regions **132**a and **132**b can be configured such that leakage current density though the portions of the Schottky contact **140** corresponding with the surface regions **132**a and **132**b is lower than that a current density through the portion of the Schottky contact **140** corresponding to the central portion of the drift region **120**, while the corresponding device still has lower barrier height and lower V_f associated with the higher doped surface regions **132**a and **132**b. Such implementations can reduce overall leakage current of the diode **100** as compared to having a uniformly, higher doped the Schottky contact **140** to achieve specific forward operating characteristics. Further in the diode **100**, the lower barrier height of the Schottky contact **140** associated with the higher doped surface regions **132**a and **132**b will reduce V_f of the diode **100** (e.g., reduce on-state conduction losses) as compared to a diode having a uniformly, lower doped surface under the Schottky contact **140** to achieve specific reverse operating characteristics. Accordingly, improved tradeoff between on-state operating characteristics and off-state operating state characteristics of a Schottky diode can be achieved by implementations of the diode **100**.

As also shown in FIG. **1**, the diode **100** includes a metal including a portion **134**a and a portion **134**b. The portion **134**a and the portion **134**b form, respectively, an Ohmic contact **144**a with the shield region **110**a, and an Ohmic contact **144**b with the shield region **110**b. In some implementations, the portions **134**a and **134**b can include the Schottky material **130** of the diode **100**. In some implementations, the portions **134**a and **134**b can include a different material, which can be deposited, annealed and/or silicided to form the Ohmic contacts **144**a and **144**b.

FIG. **2** is a diagram illustrating a cross-sectional view of another diode **200** including higher doped surface regions, according to an implementation. As with the diode **100**, in some implementations, the diode **200** can have a linear (stripe) cell layout, i.e., into and/or out of the page. In some implementations, the layout of the diode **200** can be cellular (e.g. utilizing an arrangement of geometric cells, such square, hexagonal, etc. cells), such as the example shown in FIG. **5**. The diode **200** illustrates a single diode stripe or a single diode cell, which can be interconnected with other diode stripes or diode cells to form a larger diode. Depending on the particular implementation, the spacing, sizing and arrangement of the elements of the diode **200** can be different.

As shown in FIG. **2**, the diode **200** includes a substrate **202** and a semiconductor layer **204** (semiconductor region). The substrate **202** and the semiconductor layer **204** can be of a first conductivity type, e.g., n-type conductivity. The substrate **202** can have a doping concentration that is higher than a doping concentration of the semiconductor layer **204**. In some implementations, the semiconductor layer **204** can be an epitaxial semiconductor layer, or can include multiple epitaxial semiconductor layers with different doping concentrations. That is, in the view of FIG. **2**, the upper portion of the semiconductor layer **204** can have a doping concentration that is higher than a doping concentration of the lower portion of the semiconductor layer **204**, or varies along a depth in the semiconductor layer **204**. In some implementations, the substrate **202** and the semiconductor layer **204** can include silicon carbide, or other semiconductor materials.

The diode **200** includes a shield region **210**a and a shield region **210**b that are disposed in the semiconductor layer **204**. The shield region **210**a and the shield region **210**b are disposed adjacent to a drift region **220** of the diode **200**. The shield region **210**a and the shield region **210**b of the diode **200** are of a second conductivity type that is opposite the first conductivity type, e.g., p-type conductivity. In some implementations, the first and second conductivity types can be reversed.

As with the diode **100**, the diode **200** includes a Schottky material **230** (e.g., a Schottky metal layer, or other Schottky material) that defines a Schottky contact **240** with the drift region **220**, e.g., along a surface of the drift region **220** between the shield region **210**a and the shield region **210**b. The drift region **220** includes a surface region **232**a (e.g., formed by ion implantation) and a surface region **232**b (e.g., formed by ion implantation) that are disposed in respective first and second portions of the drift region **220**, which define a Schottky contact **240** with Schottky material **230**. The diode further includes a surface region **236**a (e.g., a localized surface implant) and a surface region **236**b (e.g., a localized surface implant) that are disposed in respective third and fourth portions of the drift region **220**, and define the Schottky contact **240** with Schottky material **230**.

The surface regions **232**a and **232**b, in this example, are of the first conductivity type, and can be formed simultaneously using an ion implantation process. The surface regions **236**a and **236**b are also of the first conductivity type, and can be formed simultaneously using another ion implantation process. In the diode **200**, the surface regions **232**a and **232**b have a higher doping concentration than portions of the drift region **220** excluding such surface regions, such as the central portion, and the surface regions **236**a and **236**b have a higher doping concentration compared to the doping concentration of the surface regions **232**a and **232**b. As shown in FIG. **2**, a central (e.g., fifth) portion of the drift region **220** along the interface of the Schottky contact **240** excludes a surface region, e.g., can have an original doping concentration of the semiconductor layer **204**.

As shown in FIG. **2**, the surface region **232**a is disposed adjacent to the central upper portion of the drift region **220**, and the surface region **232**b is disposed adjacent to the central upper portion of the drift region **220**, e.g., symmetric to the surface region **232**a with respect to the central upper portion of the drift region **220**. Further, the surface region **236**a is disposed between the shield region **210**a and the surface region **232**a, and the surface region **236**b is disposed between the shield region **210**b and the surface region **232**b.

The surface regions **232**a, **232**b, **236**a and **236**b, in this example, locally, and respectively alter (lower) a barrier height of the Schottky contact **240**, as well as locally, and respectively alter (increase) associated electric fields in the portions of the drift region **220** including those surface regions. Accordingly, in this example, the Schottky barrier will be higher at the Schottky interface above the central upper portion of the drift region **220** that excludes a surface regions than a barrier height of the respective portions of the Schottky contact above the portions of the drift region **220** that include the surface regions **232**a, **232**b, **236**a and **236**b. Further, the Schottky **240** at the interface between the Schottky material **230** and the portions of the drift region including the surface regions **232**a and **232**b will have a barrier height that is greater than the barrier height of the Schottky contact at the interface above the portions of the drift region **220** including the surface regions **236**a and **236**b. That is, the portion of the Schottky contact **240** corresponding with the central portion of the drift region **220** will have a barrier height that is greater than a barrier height of the respective portions of the Schottky contact **240** corresponding with the surface regions **232**a and **232**b. Also, the barrier height of the portions of the Schottky contact **240** corresponding the surface regions **232**a and **232**b will be greater than a barrier height of the respective portions of the Schottky contact **240** corresponding with the surface regions **236**a and **236**b.

As shown in FIG. **2**, the portion of the drift region **220** excluding a surface region (e.g., a localized surface implant) can have a width W1. Further, the portion of the drift region **220** excluding a surface region, together with the portions of the drift region **220** including the surface regions **232**a and **232**, has a width of W2. In example implementations, the widths W1 and W2, and doping concentration of the surface regions **232**a, **232**b, a**36**a, **236**b can be selected based on electric field distribution at a surface of the drift region **220** (e.g., electric field distribution under reverse-bias conditions) to achieve a desired relationship between on-state and off-state operating characteristic of the diode **200**.

In this example, as W1 is varied (widened or narrowed), an associated surface area of the drift region **220** excluding a surface region on which the Schottky material **230** is disposed will vary (will respectively increase or decrease). Likewise, as W1 is varied, respective surface areas of the drift region **220** in which the surface regions **232**a, **232**b, **236**a and **236**b are disposed will also correspondingly vary. That is, increasing W1 will reduce the overall surface area of the drift region **220** in which the surface regions **232**a, **232**b, **236**a and **236**b are disposed, while decreasing W1 will increase the overall surface areas of the drift region **220** in which the surface regions **232**a, **232**b, **236**a and **236**b are disposed. Also, as W2 is varied, respective surface areas of the drift region **220** in which the surface regions **236**a and **236**b are disposed will also correspondingly vary. That is, increasing W2 will reduce the surface area of the drift region **220** in which the surface regions **236**a and **236**b are disposed, while decreasing W2 will increase the surface areas of the drift region **220** in which the surface regions **236**a and **236**b are disposed.

In the diode **200**, in the absence of regions **232**a, **232**b, **236**a and **236**b, as with the diode **100**, the electric field distribution in the drift region **220** (e.g., just below the Schottky contacts **240**) will be highest at a mid-point between the shield region **210**a and the shield region **210**b, and will decrease moving away from the mid-point, respectively, toward the shield region **210**a and the shield region **210**b (e.g., with a bell-shaped curve distribution). Accordingly, the central portion of the drift region **220** excluding a surface region will have the highest electric field for the diode **200**, while the electric field at the upper portion of the drift region **220** including the surface regions **232**a, **232**b, **236**a and **236**b will be similar, or lower.

In this example, the portion of the Schottky contact **240** corresponding with the portion of the drift region excluding a surface implant will have a higher barrier height than a barrier height of the portions of the Schottky contact **240** corresponding with the surface regions **232**a, **232**b, **236**a and **236**b. Further, the barrier height of the portions of the Schottky contact **240** corresponding with the surface regions **232**a, **232**b will greater than a higher barrier height of the portions of the Schottky contact **240** corresponding with the surface regions **236**a and **236**b. Accordingly, a tradeoff between forward operating characteristics and reverse operating characteristics of the diode **200** can be improved, e.g., as compared to having a Schottky contact interface having a constant doping concentration in the upper portion of the drift region.

For instance, in the diode **200**, the widths W1 and W2 can be adjusted such that respective leakage current density (e.g., leakage current through a specific device portion divided by a corresponding area) and/or respective on-state current densities of the portion of the Schottky contact **240** corresponding with the central portion of the drift region, and the portions of the Schottky contact **240** corresponding with the surface regions **232**a, **232**b, **236**a and **236**b are the same, or substantially the same (e.g., have a same design target). Such implementations can reduce overall leakage current of the diode **200** as compared to having a uniformly, higher doped upper portion of the drift layer below the Schottky contact **240** to achieve specific forward operating characteristics. Further in the diode **200**, the lower barrier height of the Schottky contact **240** associated with the surface regions **232**a, **232**b, **236**a and **236**b will reduce V_f of the diode **200** (e.g., reduce on-state conduction losses) as compared to a diode having a uniformly, lower doped upper portion of the drift layer below the Schottky contact **240** to achieve specific reverse operating characteristics. Accordingly, improved tradeoff between on-state operating characteristics and off-state operating state characteristics of a Schottky diode can be achieved by implementations of the diode **200**.

As also shown in FIG. **2**, the diode **200** includes a metal including a portion **234**a and a portion **234**b. The portion **234**a and the portion **234**b form, respectively, can define an Ohmic contact **244**a with the shield region **210**a, and an Ohmic contact **244**b with the shield region **210**b. In some implementations, the portions **234**a and **234**b can include the Schottky material **230** of the diode **200**. In some implementations, the portions **234**a and **234**b can include a different material (e.g., metal, such as Cu, AlCu, etc.), which can be deposited, annealed and/or silicided to form the Ohmic contacts **244**a and **244**b.

FIG. **3** is a diagram illustrating a cross-sectional view of yet another Schottky diode **300** including surface regions, according to an implementation. The diode **300** is a variation of diode **100** in FIG. **1**, and includes like and/or similar elements, which are referenced with **300** series reference numbers corresponding with the **100** series reference numbers in FIG. **1**. For instance, the diode **300** includes a substrate **302**, a semiconductor layer **304**, shield regions **310**a and **310**b, a drift region **320**, surface regions **332**a and **332**b, Schottky material **330**, a Schottky contact **340**, and metal portions **334**a and **334**b. For purposes of brevity, the similar aspects and details of the diode **300** with the diode **100** are not discussed again here.

As shown in the FIG. **3**, the diode **300** differs from the diode **100** in that the surface regions **332**a and **332**b extend over respective portions of the shield regions **310**a and **310**b. In some implementations the surface regions **332**a and **332**b can extend, respectively, over ten percent to ninety percent of the shield regions **310**a and **310**b. Such implementations can provide additional improvement in forward conduction characteristics by increasing the overall area of the Schottky contact **340**, e.g., as compared to the diode **100**, such as for a same active area of the device.

FIG. **4** is a diagram illustrating a cross-sectional view of still another Schottky diode **400** including localized drift region implants, according to an implementation. As with the diode **300**, the diode **400** is a variation of diode **100** in FIG. **1**, and includes like and/or similar elements, which are referenced with **400** series reference numbers corresponding with the **100** series reference numbers in FIG. **1**. For instance, the diode **400** includes a substrate **402**, a semiconductor layer **404**, shield regions **410**a and **410**b, a drift region **420**, surface regions **432**a and **432**b, Schottky material **430**, a Schottky contact **440**, and metal portions **434**a and **434**b. For purposes of brevity, the similar aspects and details of the diode **400** with the diode **100** are not discussed again here.

As shown in the FIG. **4**, the diode **400** differs from the diode **400** in that the interface of the Schottky contact **440** is implemented on a mesa **450** of the semiconductor layer **404**, where the mesa **450** is included in the drift region **420**. Such implementations, as with the diode **300**, can improve forward conduction characteristic by increasing area of the associated Schottky interface (e.g., area of the Schottky contact **440**).

In some implementations, the mesa **450** can be defined by forming shallow trenches where Ohmic contacts defined by the metal portions **434**a and **434**b are formed. The shape and dimensions of the mesa **450** in FIG. **4** are shown by way of illustration, and are not necessarily to scale. For instance, the mesa **450** can have a height H, which can 5 microns or less. In the diode **400**, additional resistance of the mesa **450** can be compensated for by including the surface regions **432**a and **432**b on (in, along, etc.) sidewalls of the mesa **450** in addition to portions of the upper surface of the mesa **450**.

FIG. **5** is a diagram illustrating a top-down (plan) view of still another diode **500** including localized surface regions, according to an implementation. The view of the diode **500** shown in FIG. **5** is a portion of a diode having a cellular design. For purposes of illustration, the diode **500** is illustrated without a Schottky material layer and/or metallization layers, e.g., Schottky metal and/or Ohmic contact metal, so as not to obscure the underlying structure.

In the example of FIG. **5**, the diode **500** includes hexagon shaped diode cells, where each cell includes a shield region **510**, with a drift region **520** of the diode **500** being disposed between the hexagon shaped shield regions, e.g., as segments, streets, etc., having intersections of the drift region **520** between the hexagon shaped shield regions **510**. That is, hexagon shaped drift regions surround each shield region **510**. In the diode **500**, the highest electric field will occur at these intersections of the drift region **520**, which are noted as region **540** in FIG. **5**, and are the widest portions of the drift region **520**. The diode **500** also includes an Ohmic contact region **534** disposed within the shield region **510**. In this example, a Schottky material (e.g., metal, alloy, semiconductor material, etc.) can be disposed on, and form a Schottky contact with the drift region **520**, including the regions **540**. The Schottky material can also be disposed on portions of the shield regions **510**, such as in the diodes of FIGS. **1-4**. Ohmic contacts, in the Ohmic contact regions **534**, can formed using the Schottky material, or another material, such as described herein.

In the diode **500**, the segments of the drift region **520** (e.g., the narrower or narrowest portion of the drift region **520**) between the regions **540** can include one or more surface regions that can provide desired, respective Schottky barrier heights, such as those described herein, while the regions **540** can exclude such a surface region. Accordingly, the portions of the Schottky contact in the regions **540** will have a barrier height that is greater than portions of the Schottky contact in the areas (segments) of the drift region **520** including the one or more surface regions. A width W1 of the regions **540** (analogous with the width W1 in the diode **100**) can be varied to achieve desired operating characteristics of the diode **500**. For instance, increasing W1 in the diode **500** will reduce an area of the drift region **520** of the diode **500** is which the one or more surface regions are disposed, while decreasing W1 in the diode **500** will increase an area of the drift region **520** of the diode **500** in which the one or more surface regions are disposed. In some implementations, the width W1 of the regions **540** can be selected such that leakage current density of the regions **540** is the same as, or substantially the same (e.g., has a same design target) as leakage current density of each of the segments of the drift region **520** between each region **540**. In some implementations, the width W1 of the regions **540** can be selected such that leakage current density of the regions **540** is lower than leakage current density of each of the segments of the drift region **520** between each region **540**

FIG. **6** is a diagram illustrating a cross-sectional view of a doping distribution of a diode portion **600** (e.g., half a diode cell having linear/stripe design) including a surface region, such as could be used to implement the diodes described herein. In example implementations, the diode portion **600** can be mirrored on the right and/or left to construct full and/or additional diode stripes or cells.

As shown in FIG. **6**, the diode portion **600** includes a semiconductor layer **604** of the first conductivity type (e.g., n-type conductivity) and a shield region **610** of the second conductivity type (e.g., p-type conductivity). In some implementations, these conductivity types can be reversed. A Schottky material **630** is disposed on, and forms a Schottky contact **640** with a drift region **620**, and is also disposed on a portion of the shield region **610**. The diode portion **600** also includes a surface region **632** that is adjacent to the shield region **610**. As shown in FIG. **6**, a portion of the drift region **620** excluding the surface region **632** has a width of 0.5 W1, e.g., half the width W1 in FIG. **1**, as the diode portion **600** is a half diode segment or cell. As in the diode

100 of FIG. **1**, a portion of the Schottky contact **640** corresponding the portion of the drift region **620** excluding the surface region **632** will have a barrier height that is greater than a barrier height of a portion of the Schottky contact corresponding with the surface region **632**. Metal defining an Ohmic contact with the shield region **610** is omitted in FIG. **6**.

FIG. **6** illustrates relative doping concentrations for both the first conductivity type (e.g., n-type) and the second conductivity type (e.g., p-type) for the diode portion **600**. For instance, areas of relative doping concentration for the first conductivity type are indicated for the semiconductor layer **604**, including the drift region **620** of the diode portion **600**, and for the surface region **632**. In this example, areas of relative doping concentration for the second conductivity type are indicated in the shield region **610**. In some implementations, the doping concentration of the surface region **632** (e.g., at the interface of the Schottky contact **640**) can be to 1000 times higher than the doping concentration of the drift region **620** (e.g., at the interface of the Schottky contact **640** excluding the surface region **632**). In this example, doping concentration in the shield region **610** can be higher at the surface of the semiconductor layer **604**, and decrease with depth in the semiconductor layer **604**. Such doping concentrations will depend on the specific implementation.

In FIG. **6**, distance in arbitrary units (A.U.) is shown on the x-axis and depth in A.U. is shown on the y-axis. The distance and depth in FIG. **6** are shown by way of reference, and will vary depending on the particular implementation. In the example of FIG. **6**, distance along the x-axis indicates left to right distance along the diode portion **600** and corresponds with distance A.U. for a graph of electric field distribution for implementations of the diode portion **600** shown in FIG. **7** and distance A.U. for the doping concentration profiles of FIG. **8**. The depth A.U. in FIG. **6** indicates depth in the semiconductor layer **604**, which can be a portion of an epitaxial semiconductor layer, such as those described herein. The depth A.U. in FIG. **6** corresponds with depth A.U. in FIG. **8**

FIGS. **7-10** are graphs illustrating various operating characteristics and aspects of implementations of diodes including Schottky contacts with surface regions, such as implementations of the diode **100** of FIG. **1** (e.g., using the diode portion **600**). The aspects of FIGS. **7-10** described below can, however, similarly apply to other diodes, such as the example diode implementations described herein.

FIG. **7** is a graph **700** illustrating electric field distributions for various implementations of the diode portion **600** of FIG. **6** (or the diode **100** of FIG. **1**) under reverse-bias conditions with varying width W1. FIG. **8** is a graph **800** illustrating examples of doping concentrations (e.g., trace **810** and trace **820**) versus depth in the surface region (from the Schottky contact interface) for diode implementations with surface regions (e.g., formed using ion implantation). FIG. **9** is graph **900** illustrating IV curves (e.g., forward operating characteristics) for implementations of the diode of FIG. **1**, e.g., based on the diode portion **600**, compared to a prior diode implementation. FIG. **10** is a graph **1000** illustrating forward voltage drop for diode implementations illustrated in FIG. **9**.

Referring to FIG. **7**, electric field distributions along a semiconductor surface under a Schottky contact are shown for various implementations of the diode portion **600**, with varying width W1, under reverse bias conditions. The applied reverse-bias voltage will vary depending on the particular implementation. In some implementations, the reverse-bias voltage can be 500 volts (V) or greater. The trace **710** illustrates an implementation of a diode with no surface region (e.g., W1 is equal to a width of the drift region bounded by shield regions) and the trace **760** illustrates an implementation of the diode portion **600** where the width W1 is zero (e.g., the entire drift region has a high doping concentration surface region). Traces **720**, **730**, **740** and **750** illustrate implementations of the diode portion **600**, where the width W1 is greater than zero and less than the width of the upper portion of the drift region bounded by the shield regions. The specific values for the width W1 will depend on the particular implementation, such as a width of the diode's drift region. That is, the specific values of the width W1 illustrated by FIG. **7** can be proportional to a width of a corresponding diode's upper portion of the drift region.

The traces **710-760** shown in FIG. **7** illustrate electric fields in the various implementations of the diode portion **600** just below an upper surface of the semiconductor layer **604** (e.g. 5 nm below the upper surface). As noted above, the distance A.U. along the x-axis in FIG. **7** corresponds with the distance A.U. along the x-axis in FIG. **6** for the diode portion **600**. Electric field, as a function of distance, is shown on the y-axis in A.U.

As shown by the trace **710**, the implementation of a diode with no surface region has the lowest, or similar electric field along the y-direction, which can indicate higher conduction losses than the diode implementations with surface regions illustrated in FIG. **7**, e.g., by the traces **720-760**. However, the peak **770** of the electric field for the trace **710** can indicate an upper limit for electric field for a given diode structure (e.g., with or without surface regions). Accordingly, the traces **720** and **730** illustrate diodes with surface regions with electric field that is higher at some locations along y-axis than that shown by the trace **710** (e.g., will have lower conduction losses) but do not exceed the peak **770**. The electric fields depicted by the traces **740-770** (e.g., at their respective peak electric field) all exceed the peak **770**, which could result in high leakage currents and potentially excessive power dissipation during reverse bias operation that can lead to degradation of device characteristics and/or catastrophic failure. Accordingly, such electric field distribution information can be used to select an appropriate value for the width W1 in a corresponding diode implementation, such as the diode **100**, where improvement in on-state performance characteristics can be achieved without deterioration of a corresponding diode's reverse/blocking characteristics.

Referring to FIG. **8**, the graph **800** illustrates doping concentration profiles for example localized surface implants that can be used in the diode implementations described herein. As noted above, the distance A.U. along the x-axis of FIG. **8** corresponds with the distance A.U. of FIG. **6**, and the depth A.U. along the y-axis in FIG. **8** corresponds with the depth A.U. of FIG. **6**. In FIG. **8**, a trace **810** illustrates a doping concentration distribution for a surface region formed by ion implantation through a film (layer) of another material disposed on a surface of the semiconductor layer or by diffusion methods, and a trace **820** illustrates an example of doping concentration distribution for a surface region formed using ion implantation without such a film on a surface of the semiconductor layer. In implementations such as the example illustrated by the trace **810**, the film can be removed after forming the implant. The film can be a screen oxide such as a thermal oxide, a deposited oxide, or could be a layer of another implant screen material. The choice of surface region formation depends on device design specifications and process compatibility.

Referring to FIG. **9**, a graph **900** illustrating IV curves (forward operating characteristics) for various Schottky diode implementations, such as implementation of the diode **100** with the diode portion **600**, is shown. In the graph **900**, voltage (forward voltage) is shown along the x-axis in A.U., and current is shown along the y-axis in A.U. In the graph **900**, the trace **910** shows forward IV characteristics for a Schottky diode without surface regions (e.g., the width W1 is equal to a width of the upper portion of the drift region).

In FIG. **9**, traces **920**, **930**, **940**, **950** and **960** illustrate forward operating characteristics (IV characteristics) for implementations of the diode **100**, where the width W1 is less than a width of the upper portion of the drift region, and as the width W1 decreases for different designs (as indicated in FIG. **9**) and the area of the drift region **120** in which the surface regions **132***a* and **132***b* are disposed increases. The diode implementations illustrated by the traces **910-960**, in this example, can correspond with the diode implementations illustrated by the traces **710-760** in FIG. **7**. As shown in FIG. **9**, as W1 decreases, current for a given forward voltage increases, illustrating the benefit of the approaches described here of using surface regions in a Schottky diode's drift region for improving the tradeoff between forward operating characteristics and reverse operating characteristics.

Referring to FIG. **10**, a graph **1000** illustrating the dependence of forward voltage drop V f (at a fixed forward current density) on the width W1 for implementations of the diode **100**, such as those that can correspond with illustrated by the traces **920-960** in FIG. **9** is shown. In FIG. **10**, the width W1 is shown along the x-axis in A.U., while corresponding V_f values are shown on the y-axis in A.U. As shown in FIG. **10**, as W1 decreases, V_f also decreases. In the graph **1000**, in this example, the points **1020** and **1030** correspond respectively with the traces **720** and **730** in FIG. **7**, and traces **920** and **930** in FIG. **9**. In this example, the point **1020** can represent approximately e.g., a four percent reduction in V_f as compared to the diode implementation illustrated by the trace **910** (e.g., a diode that does not include surface regions), while the point **1030** can represent approximately e.g., an eight percent reduction in V_f as compared to the diode implementation illustrated by the trace **910**. Such reductions in V_f can allow for reducing an overall size of a Schottky diode to achieve a desired forward operation current density, which can reduce overall manufacturing costs.

FIG. **11A-11C** are diagrams illustrating cross-sectional views of an example method for forming surface regions in a Schottky diode. For purposes of illustration, the approach of FIGS. **11A-11C** will be described with reference to the structure of the diode portion **600** in FIG. **6**. Referring to FIG. **11A**, a mask **1115** can be formed on a surface of the semiconductor layer **604**. After forming the mask **1115**, a deep, high energy implant (e.g., p-type implant) can be performed to form the shield region **610**. The mask **1115** can then be removed and an implant mask **1125** can be formed, where the mask **1125** can be used for forming a localized surface (drift region) implant **1132** (which can correspond with implant **632** in FIG. **6**). The implant mask **1125** can then be removed and the Schottky material **630** and/or metal **634** can be formed to define Schottky and Ohmic contacts. In some implementations, the mask **1125** can be formed from mask **1115**, e.g., using self-aligned techniques, such as an etch-back process and/or a spacer process.

FIG. **12A-12D** are diagrams illustrating cross-sectional views of another example method for forming surface regions in a Schottky diode. As with FIGS. **11A-11C**, for purposes of illustration, the approach of FIGS. **12A-12D** will be described with reference to the structures of the diode **300** in FIG. **3** and the diode portion **600** in FIG. **6**. Referring to FIG. **12A**, a mask **1215** can be formed on a surface of the **604**. After forming the mask **1215**, a deep, high energy implant (e.g., p-type implant) can be performed to form a buried portion **610***a* of the shield region **610**. The mask **1215** can then be removed and a mask **1225** can be formed, where the mask **1225** can be used for forming a localized surface (drift region) implant **1232** (which can correspond with surface regions **332***a* and **332** in FIG. **3**, extending, respectively over the shield regions **310***a* and **310***a*, or the shield region **610** in FIG. **6**). The mask **1225** can then be removed and the mask **1235** can be formed, where the mask **1235** can be used for forming an upper portion **610***b* of the shield region **610** The mask **1225** can then be removed and the Schottky metal **630** and/or metal **634** can be formed to define Schottky and Ohmic contacts. In this example, the mask **1225** and/or the mask **1235** can be formed using self-aligned semiconductor processes. For instance, in some implementations, the mask **1225** can be formed from mask **1215**, e.g. using an etch-back process. Also, in some implementations, the mask **1235** can be formed from the mask **1225** e.g., using a spacer process.

FIG. **13A-13C** are diagrams illustrating cross-sectional views of yet another example method approach for forming surface regions in a Schottky diode. As with FIGS. **11A-11C** and **12A-12D**, for purposes of illustration, the approach of FIGS. **13A-13C** will be described with reference to the structure of the diode portion **600** in FIG. **6**. Referring to FIG. **13A**, a mask **1315** can be formed on a surface of the semiconductor layer **604**. After forming the mask **1315**, a deep, high energy implant (e.g., p-type implant) can be performed to form the shield region **610**. The implant mask **1315** can then be removed and a mask **1325** can be formed, where the mask **1325** can be a sloped mask and can be used for forming a surface region **1332** where the doping concentration of the implant **1332** can gradually vary along the surface and/or along a depth of the implant **1332** in the semiconductor layer **604**. The implant mask **1325** can then be removed, and the Schottky metal **630** and/or metal **634** can be formed to define Schottky and Ohmic contacts. In some implementations, the mask **1325** can be formed using a photoresist reflow process and/or a gray scale photolithography process.

In the approaches described herein, such as in the processing approaches of FIGS. **11A-11C**, **12A-12D** and **13A-13**, surface regions can be formed using an ion implantation with an implantation beam energy of 50 keV or less and an implant dose (e.g., p-type dose) of 1×10^{12} cm^{-2} to 1×10^{14} cm^{-2}. In some implementation, different beam energies, implant doses, masking techniques, doping techniques (e.g., diffusion), and so forth can be used. The specific beam energy and dose used can depend, at least in part, on the semiconductor material used, e.g., silicon, SiC, etc.

It will be understood that, in the foregoing description, when an element, such as a layer, a region, a substrate, or component is referred to as being on, connected to, electrically connected to, coupled to, or electrically coupled to another element, it may be directly on, connected or coupled to the other element, or one or more intervening elements may be present. In contrast, when an element is referred to as being directly on, directly connected to or directly coupled to another element or layer, there are no intervening elements or layers present. Although the terms directly on, directly connected to, or directly coupled to may not be used throughout the detailed description, elements that are shown as being directly on, directly connected or directly coupled can be referred to as such. The claims of the application, if any, may be amended to recite exemplary relationships described in the specification or shown in the figures.

As used in the specification and claims, a singular form may, unless definitely indicating a particular case in terms of the context, include a plural form. Spatially relative terms (e.g., over, above, upper, under, beneath, below, lower, and so forth) are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. In some implementations, the relative terms above and below can, respectively, include vertically above and vertically below. In some implementations, the term adjacent can refer to regions that are laterally adjacent to or horizontally adjacent to one another, e.g., in contact with, such as in a semiconductor material, semiconductor layer, and/or semiconductor region.

Some implementations may be implemented using various semiconductor processing and/or packaging techniques. Some implementations may be implemented using various types of semiconductor processing techniques associated with semiconductor substrates including, but not limited to, for example, Silicon (Si), Gallium Arsenide (GaAs), Gallium Nitride (GaN), Silicon Carbide (SiC), and/or so forth.

While certain features of the described implementations have been illustrated as described herein, many modifications, substitutions, changes and equivalents will now occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the scope of the implementations. It should be understood that they have been presented by way of example only, not limitation, and various changes in form and details may be made. Any portion of the apparatus and/or methods described herein may be combined in any combination, except mutually exclusive combinations. The implementations described herein can include various combinations and/or sub-combinations of the functions, components and/or features of the different implementations described.

While certain features of the described implementations have been illustrated as described herein, many modifications, substitutions, changes and equivalents will now occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the scope of the embodiments.

What is claimed is:

1. A diode comprising:

a substrate of a first conductivity type;

a semiconductor layer of the first conductivity type disposed on the substrate, the semiconductor layer including a drift region of the diode;

a shield region of a second conductivity type disposed in the semiconductor layer adjacent to the drift region;

a surface region of the first conductivity type disposed in a first portion of the drift region adjacent to the shield region, the surface region having a doping concentration that is greater than a doping concentration of a second portion of the drift region adjacent to the surface region, the second portion of the drift region excluding the surface region, the surface region being further disposed in ten percent to ninety percent of an area of an upper portion of the shield region; and

a Schottky material disposed on:

at least a portion of the shield region;

the surface region in the first portion of the drift region; and

the second portion of the drift region.

2. The diode of claim **1**, wherein the surface region is disposed between the shield region and the second portion of the drift region.

3. The diode of claim **1**, wherein the surface region is a first surface region, the diode further comprising:

a second surface region of the first conductivity type disposed in a third portion of the drift region, the second surface region being disposed adjacent to the first surface region, the second surface region having a doping concentration that is greater than the doping concentration of the second portion of the drift region and less than the doping concentration of the first surface region,

the Schottky material being further disposed on the second surface region.

4. The diode of claim **3**, wherein the second surface region is further disposed between the first surface region and the second portion of the drift region.

5. The diode of claim **1**, wherein:

the diode includes an arrangement of geometrically shaped cells;

a widest portion of the drift region excludes the surface region; and

a narrowest portion of the drift region includes the surface region.

6. The diode of claim **1**, wherein:

the first conductivity type is n-type; and

the second conductivity type is p-type.

7. The diode of claim **1**, wherein:

the substrate is a silicon carbide substrate; and

the semiconductor layer is an epitaxial silicon carbide layer,

the substrate having a doping concentration that is higher than a doping concentration of the epitaxial silicon carbide layer.

8. The diode of claim **1**, wherein the semiconductor layer includes:

a first epitaxial semiconductor layer of the first conductivity type, the first epitaxial semiconductor layer being disposed on the substrate; and

a second epitaxial semiconductor layer of the first conductivity type, the second epitaxial semiconductor layer being disposed on the first epitaxial semiconductor layer,

the first epitaxial semiconductor layer having a doping concentration that is greater than a doping concentration of the second epitaxial semiconductor layer.

9. The diode of claim **1**, wherein the at least a portion of the shield region is a first portion of the shield region, the diode further comprising:

a metal disposed on a second portion of the shield region and defining an ohmic contact to the shield region.

10. The diode of claim **9**, wherein the metal disposed on the second portion of the shield region includes at least one of:

the Schottky material;

a metal silicide; or

a deposited metal.

11. The diode of claim **1**, wherein the surface region has a depth in the semiconductor layer of 100 nanometers (nm) or less.

12. The diode of claim **1**, wherein the surface region is disposed in ten percent to ninety percent of an area of an upper portion of the drift region.

13. The diode of claim **1**, wherein the doping concentration of the surface region varies along at least one of:

a surface of the semiconductor layer; or

a depth of the surface region in the semiconductor layer.

14. A diode comprising:

a substrate of a first conductivity type;

a semiconductor layer of the first conductivity type disposed on the substrate, the semiconductor layer including a drift region of the diode;

a first shield region of a second conductivity type disposed in the semiconductor layer adjacent to the drift region;

a second shield region of the second conductivity type disposed in the semiconductor layer adjacent to the drift region, the drift region being disposed, at least in part between the first shield region and the second shield region;

a surface region of the first conductivity type disposed in a first portion of the drift region between the first shield region and the second shield region, the surface region having a doping concentration that is greater than a doping concentration of a second portion of the drift region adjacent to the surface region, a second portion of the drift region excluding the surface region, the surface region being further disposed in ten percent to ninety percent of an area of an upper portion of the first shield region and in ten percent to ninety percent of an area of an upper portion of the second shield region; and

a Schottky material disposed on:

at least a portion of the first shield region;

at least a portion of the second shield region;

the surface region in the first portion of the drift region; and

the second portion of the drift region.

15. The diode of claim **14**, wherein the surface region is further disposed:

between the first shield region and the second portion of the drift region; and

between the second shield region and the second portion of the drift region.

16. The diode of claim **14**, wherein the surface region is a first surface region, the diode further comprising:

a second surface region of the first conductivity type disposed in a third portion of the drift region, the second surface region including:

a first portion disposed between the first shield region and a first portion of the first surface region; and

a second portion disposed between the second shield region and a second portion of the first surface region,

the second surface region having a doping concentration that is greater than the doping concentration of the second portion of the drift region and less than the doping concentration of the first surface region,

the Schottky material being further disposed on the second surface region.

17. The diode of claim **16**, wherein the second portion of the drift region is disposed between the first portion of the first surface region and the second portion of the first surface region.

18. A method for forming a diode, the method comprising:

forming a semiconductor layer of a first conductivity type disposed on a substrate of the first conductivity type, the semiconductor layer including a drift region of the diode;

forming a shield region of a second conductivity type in the semiconductor layer adjacent to the drift region;

forming a surface region of the first conductivity type in a first portion of the drift region adjacent to the shield region and in ten percent to ninety percent of an area of an upper portion of the shield region, the surface region having a doping concentration that is greater than a doping concentration of a second portion of the drift region adjacent to the surface region, the second portion of the drift region excluding the surface region; and

depositing a Schottky material disposed on:

at least a portion of the shield region;

the surface region in the first portion of the drift region; and

the second portion of the drift region.

19. The method of claim **18**, wherein the doping concentration of the surface region varies along at least one of:

a surface of the semiconductor layer; or

a depth of the surface region in the semiconductor layer.

20. The method of claim **18**, wherein the surface region is a first surface region, the method further comprising:

forming a second surface region of the first conductivity type in a third portion of the drift region, the second surface region being disposed adjacent to the first surface region, the second surface region having a doping concentration that is greater than the doping concentration of the second portion of the drift region and less than the doping concentration of the first surface region,

the Schottky material being further disposed on the second surface region.

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