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TRANSISTORS WITH SELF-ALIGNED SOURCE-CONNECTED FIELD PLATES

Abstract

Placement of a field plate in a field-effect transistor is optimized by using multiple dielectric layers such that a first end of field plate is separated from a channel region of the transistor by a first set of one or more distinct dielectric material layers. A second end of the field plate overlies the channel region and a control electrode from which it is separated by the first set of dielectric layers and one or more additional dielectric layers. Relative positioning of the control electrode and the field plate are determined by a single processing step such that the field plate is self-aligned to the control electrode in order to reduce variations in transistor performance associated with manufacturing process variations.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION [0001] This application is a divisional of co-pending U.S. patent application Ser. No. 17/645,290, filed on Dec. 20, 2021.

FIELD OF THE INVENTION

[0002] Embodiments of the subject matter described herein relate generally to semiconductor devices with conductive elements and methods for fabricating such devices.

BACKGROUND OF THE INVENTION

[0003] Semiconductor devices find application in a wide variety of electronic components and systems. High power, high frequency transistors find application in radio frequency (RF) systems and power electronics systems. Gallium nitride (GaN) device technology is particularly suited for these RF power and power electronics applications due to its superior electronic and thermal characteristics. In particular, the high electron velocity and high breakdown field strength of GaN make devices fabricated from this material ideal for RF power amplifiers and high-power switching applications. Field plates are used to reduce gate-drain feedback capacitance and to increase device breakdown voltage in high frequency transistors. Accordingly, there is a need for semiconductor devices, and GaN devices in particular, with field plates.

SUMMARY OF THE INVENTION

[0004] In an example embodiment, a method of fabricating a semiconductor device is provided. The method includes depositing first electrically conductive material over a first dielectric layer. The first dielectric layer overlies a channel region of a semiconductive substrate suitable for use as a semiconductive transistor channel. The method also includes, simultaneously forming, during a first patterning step, first, second, and third conductive elements above the channel region. The first, second, and third conductive elements are electrically isolated from each other and the second conductive element is disposed between the first conductive element and the third conductive element. The first, second, and third conductive elements are formed by selectively removing a portion of the first electrically conductive material.

[0005] The method also includes depositing second dielectric material over the first, second, and third conductive elements, and over the first dielectric layer; and, during a second patterning step, forming a first aperture between the first and second conductive elements that passes through the first dielectric layer and the second dielectric material. The first aperture is formed by selectively removing a first portion of the second dielectric material to leave remaining second dielectric material; and removing a portion of the first dielectric layer above the channel region in an area between the first and second conductive elements.

[0006] The method also includes forming an electrically conductive control electrode; forming a second aperture that passes through the second dielectric material; and forming an electrically conductive field plate interconnect. The control electrode electrically contacts the first and second conductive elements and extends within the first aperture. The second aperture is formed during a third patterning step. The field plate interconnect extends within the second aperture and electrically contacts the third conductive element within the second aperture.

[0007] In another example embodiment, a semiconductor device is provided. The device includes a channel region defined in a semiconductor substrate, a first current terminal electrically coupled to

a first end of the channel region, and a second current terminal electrically coupled to a second end of the channel region. The device has a first dielectric layer having a first dielectric thickness that overlies the channel region and a first aperture in the first dielectric layer that overlies the channel region. The device also includes an electrically conductive control electrode, an electrically conductive field plate electrode, and at least an electrically conductive first electrode extension. The device is configured to provide an electrically conductive path from the first current terminal to the second current terminal via the channel region when a sufficient control voltage is applied to the control electrode.

[0008] The control electrode extends within the first aperture and is configured to be electrically coupled to the channel region. The first electrode extension is adjacent to the first aperture, contacts a first side of the control electrode, and at least partially overlies the first dielectric layer. The first electrode extension and the field electrode are each formed from the same electrically conductive material.

[0009] In one or more embodiments, the device also includes an electrically conductive second electrode extension opposite the first electrode extension that is also adjacent to the first aperture, at least partially overlies the first dielectric layer, and contacts a second side of the control electrode opposite the first side of the control electrode. In such embodiments the second electrode extension is formed from the same electrically conductive material as the first electrode extension and the field plate electrode.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The present disclosure is illustrated by way of examples, embodiments and the like and is not limited by the accompanying figures, in which like reference numbers indicate similar elements. Elements in the figures are illustrated for simplicity and clarity and have not necessarily been drawn to scale. The figures along with the detailed description are incorporated and form part of the specification and serve to further illustrate examples, embodiments and the like, and explain various principles and advantages, in accordance with the present disclosure, wherein:

[0011] FIG. 1 is a cross-sectional schematic illustration of an example transistor according to embodiments herein.

[0012] FIGS. 2A-2E are cross-sectional schematic illustrations of the transistor of FIG. 1 during various steps of an example process for fabricating transistors according to embodiments herein.

[0013] FIG. 3 is a cross-sectional schematic illustration of an example transistor similar to the transistor of FIG. 1 according to embodiments herein.

[0014] FIG. 4 is a cross-sectional schematic illustration of an example transistor similar to the transistor of FIG. 1 according to embodiments herein

[0015] FIGS. 5A and 5B are cross-sectional schematic illustrations of an example transistor according to embodiments herein depicted with various features shown roughly to scale.

[0016] FIG. 6 is a cross-sectional schematic illustration showing an example transistor gate according to embodiments herein with various features roughly to scale.

DETAILED DESCRIPTION

[0017] The following detailed description provides examples for the purposes of understanding and is not intended to limit the invention or the application and uses of the same. Furthermore, there is no intention to be bound by any expressed or implied theory presented in the preceding technical field, background, or the following detailed description.

[0018] For simplicity and clarity of illustration, the drawing figures illustrate the general manner of construction, and descriptions and details of well-known features and techniques may be omitted to avoid unnecessarily obscuring the invention. Additionally, elements in the drawing figures are not

necessarily drawn to scale. For example, the dimensions of some of the elements or regions in the figures may be exaggerated relative to other elements or regions to help improve understanding of embodiments of the invention.

[0019] The terms “first,” “second,” “third,” “fourth” and the like in the description and the claims, if any, may be used for distinguishing between similar elements and not necessarily for describing a particular sequential or chronological order. It is to be understood that the terms so used are interchangeable under appropriate circumstances such that the embodiments of the invention described herein are, for example, capable of operation in sequences other than those illustrated or otherwise described herein. Furthermore, the terms “comprise,” “include,” “have” and any variations thereof, are intended to cover non-exclusive inclusions, such that a process, method, article, or apparatus that comprises a list of elements is not necessarily limited to those elements but may include other elements not expressly listed or inherent to such process, method, article, or apparatus. The term “coupled,” as used herein, is defined as directly or indirectly connected in an electrical or non-electrical manner. As used herein the terms “substantial” and “substantially” mean sufficient to accomplish the stated purpose in a practical manner and that minor imperfections, if any, are not significant for the stated purpose.

[0020] Directional references such as “top,” “bottom,” “left,” “right,” “above,” “below,” and so forth, unless otherwise stated, are not intended to require any preferred orientation and are made with reference to the orientation of the corresponding figure or figures for purposes of illustration.

[0021] It will be appreciated that the steps of various processes described herein are non-limiting examples of suitable processes according to embodiments and are for the purposes of illustration. Devices according to embodiments herein may be fabricated using any suitable processes including those that omit steps described above, perform those steps and similar steps in different orders, and the like. It will also be appreciated that well-known features of transistors may be omitted for clarity. For example, the Figures may not show additional dielectric layers and vias which may be present in one or more embodiments

[0022] FIG. 1 is a cross-sectional schematic view of example transistor **100** provided with an electrode suitable for use as a field plate according to embodiments herein (a field plate **150**). The transistor **100** is formed on a semiconductor substrate **102** and has a channel region **110** near a top surface **112**. The transistor includes a first current terminal **120** electrically coupled to a first end of the channel region **110** and a second current terminal **125** electrically coupled to a second end of the channel **110** opposite the first current terminal **120**. A first dielectric material **115** is disposed on the top surface **112** overlying the channel region **110**. The first current terminal **120** and the second current terminal **125** may be formed by any suitable method. For example, they may be appropriately doped regions within the semiconductor substrate **102**, or as metallic contacts deposited within recesses in the substrate **102** or on the surface of the substrate **102**.

[0023] An electrically conductive first electrode (hereinafter a control electrode **130**) contacts the channel region **110** through an aperture in the first dielectric material **115**. As shown, the control electrode **130** may have a first section **132** that contacts the channel region **110** within the aperture and optionally has a second section **134** that overhangs the first dielectric material **115**. Although the control electrode **130** is depicted as having vertical sidewalls, it will be understood that the control electrode **130** may have any suitable geometry. For instance, the first section **132** of the control electrode may have sidewalls that are curved or slanted (see FIG. 4A, FIG. 4B and FIG. 5 as non-limiting examples). Similarly, the second section **134** of the control electrode **130** may have sidewalls that are curved or slanted and the top surface (farthest from the channel region **110**) may have any suitable geometry. The control electrode **130** is disposed in between the first current terminal **120** and the second current terminal **125** along the length of the channel region **110**. The control electrode **130** is flanked by conductive elements **135** which serve as extensions of the control electrode **130**. These extensions may also be referred to as gate field plates.

[0024] It will be appreciated that the first current terminal **120** may be operated, for example, as a

source terminal of the transistor **100** and the second current terminal **125** may be operated, for example, as a drain terminal of the transistor **100**. It also be understood that the control electrode **130** is suitable for use as a control electrode of the transistor **100** such that, when a suitable bias voltage is applied to the control electrode **130**, the channel region **110** is configured to provide an electrically conductive path between the first current terminal **120** and the second current terminal **125** (i.e., between the source and drain of the transistor **100**). It will be appreciated that the current terminals **120,125** may have any acceptable geometry and that, in one or embodiments, the current terminals **120,125** are provided with conductive electrodes that contact the current terminals **120,125** which are not explicitly shown.

[0025] Additional dielectric material **140** overlies the control electrode **130** and various portions of the channel region **110**. As shown in FIG. **1**, this additional dielectric material **140** may include a second dielectric material **140a** material and a third dielectric material **140b** as shown in FIG. **1**. It will be understood that, in one or more embodiments, the dielectric material **140a** is the same as the dielectric material **140b** or substantially similar to the dielectric material **140a**. For instance, the dielectric materials **140a, 140b** may be deposited at different times using the same process and the same or similar source materials. As a further example, the dielectric materials may both be an RF-sputtered oxide or nitride material. It will also be understood that in one or more embodiments, the dielectric materials **140a, 140b** are different materials (e.g., the dielectric material **140a** may be silicon nitride while the dielectric material **140b** may be silicon oxide or aluminum oxide).

[0026] As shown in FIG. **1**, the transistor **100** also includes a second electrode formed by conductive element (hereinafter a field plate **150**) disposed above the channel region **110** in between the control electrode **130** and the second current terminal **125**. An electrically conductive interconnect **160** overlies the control electrode **130** and has a first end **162** that is electrically coupled to the field plate **150** and a second end **164** that is electrically couples the first end **162** (and the field plate **150**) to the first current terminal **120**. In one or more embodiments, the interconnect **160** may be continuous along the width of a gate finger perpendicular to the cross section plane of FIG. **1**. In one or more embodiments, the connection may only occur in portions of the gate finger width.

[0027] It will be understood that, when the first current terminal **120** is operated as a source terminal of the transistor **100**, the field plate **150** is configured to operate as source-coupled field plate. In the transistor **100**, the conductance of the channel region **110** during operation of the transistor **100** will be influenced by the electrical potential of the control electrode **130** and the field plate **150**. It will be appreciated that the field plate **150** is capacitively coupled to the channel region **110** across the first dielectric material **115**. Meanwhile the interconnect **160** is separated from the control electrode **130** by the dielectric material **140** and from the channel region **110** by both the dielectric material **140** and the dielectric material **115**.

[0028] Generally, a source-coupled field plate such as the field plate **150** may be used to reduce gate-to-drain feedback capacitance (“C.sub.GD”) in transistors such as the transistor **100** when compared to otherwise similar transistors lacking such a field plate. However, the addition of a source-coupled field plate spaced apart from a control electrode such as the control electrode **130** will also tend to introduce additional capacitance between the gate and the source (“C.sub.GS”) which may be an undesirable trade-off. Often, a single dielectric may be deposited over a substrate that has already been provided with a channel region and a gate. In this instance, both the C.sub.GD reduction provided by a source field plate and the increased C.sub.GS associated with the field plate will depend strongly on the thickness and dielectric properties of that single dielectric layer.

[0029] Meanwhile, in the transistor **100**, the placement of the field plate **150** as shown and described may confer certain advantages. Specifically, the relative dielectric constants and thicknesses of the dielectric material **115** and the dielectric material **140** may be chosen to achieve particular performance characteristics and to facilitate various fabrication procedures in

embodiments herein. As an example, if the field plate **150** were formed above the dielectric material **140** (as in other transistors), both the C.sub.GD reduction achieved and the additional C.sub.GS introduced would depend upon the thickness and dielectric properties of the dielectric material **140**. But in the example of FIG. **1**, the field plate **150** is separated from the channel region **110** only by the dielectric material **115**. This dielectric material **115** may be comparatively thin (i.e., thinner than all or part of the dielectric material **140**) and/or have a relatively high dielectric constant (i.e., a dielectric constant that is higher than the dielectric constant of all or part of the dielectric material **140**). Meanwhile, the additional C.sub.GS introduced will depend on the thickness and dielectric properties of the dielectric material **140** (i.e., the dielectric materials **140a**, **140b**). It will be appreciated that, in one or more embodiments, the dielectric material **140** may be configured to be thicker than the dielectric material **115** and/or to have a lower dielectric constant, thereby maximizing the C.sub.GD reduction achieved relative to the additional C.sub.GS introduced by the field plate **150** and interconnect **160**.

[0030] As an example, in one or more embodiments, the dielectric material **115** is silicon nitride (SiN or SiN.sub.X where X is a fractional value other than one) and has a thickness in a range from 10 nm to 300 nm. As a further example, in one or more embodiments, the dielectric material **140** is silicon oxide (SiO.sub.2 or SiO.sub.X, where X is a fractional value other than two) and has a thickness in a range from 50 nm to 5000 nm. In one or more other embodiments (as described further below in connection with FIG. **4**, dielectric material **115** may be deposited, to provide a first thickness underneath conductive elements **135**, and a second thickness underneath at least a portion of the field plate **150** to facilitate independent optimization of their functions. For example, a thicker dielectric underneath the drain side of field plate **150** can be employed to yield a better trade-off between reducing C.sub.GD and increasing C.sub.DS. Such an arrangement may have the advantage of reducing the peak electric field strength in the channel region during operation of a transistor such as the transistor **100**, resulting in improved breakdown voltage characteristics.

[0031] It will be understood that features of the transistor **100** above (and features of other example transistors herein) may be compatible with various transistor technologies. For instance, the transistor **100** and/or any other example transistor according to embodiments herein may be a MOSFET or MISFET fabricated on a silicon substrate or any other suitable semiconductor substrate. For instance, In one or more embodiments, the transistor **100** is a III-V compound semiconductor-based high-electron-mobility transistor (“HEMT”), otherwise known as a heterostructure field effect transistor (“HFET”). In such embodiments the effective semiconductor channel may be a 2D electron gas (“2DEG”) formed at a semiconductor heterojunction disposed within the channel region **110** according to known techniques. In one or more embodiments, the transistor **100** may be a gallium-nitride (GaN) based HEMT. In some such embodiments, a 2DEG is formed at an interface between a GaN layer and an aluminum doped layer with a stoichiometric composition described by the chemical formula Al.sub.xGa.sub.1-xN. It will be understood that in some such embodiments the effective channel through which current conduction occurs may be buried within the channel region **110** and may not extend to the top surface **112** of the channel region **110**. In one or more embodiments, the first dielectric material **115** may be a material that provides surface passivation for the channel region **110**. For instance, the first dielectric material **115** may be a silicon nitride passivation layer over a GaN-based heterostructure.

[0032] FIGS. **2A-2E** illustrate steps in an example process **200** for fabricating a transistor with a source-coupled field plate according to embodiments herein. For purposes of illustration, the process **200** is described with respect to fabrication of the transistor **100** of FIG. **1**. It should be understood that use of the process **200** may confer additional advantages beyond those described in connection with FIG. **1**.

[0033] Specifically, the performance of a transistor such as the transistor **100** may be sensitive to the relative distance of the field plate **150** to the control electrode **130** and to the surface area of the field plate **150** above the channel region **110** relative to the surface area of the first section **132** of

the control electrode **130** above the channel **110**. In other approaches, patterning of the control electrode **130** and the field plate **150** may be performed independently (e.g., during two separate lithographic steps), which case the separation between the control electrode **130** and the field plate **150** will be subject to interlayer alignment tolerances of the fabrication process. In some instances, this may lead to undesirable variation in the performance of individual transistors fabricated on separate wafers and potentially between transistors fabricated on the same wafer (e.g., if there is a misalignment between the relevant lithographic steps. Process flows that can reduce part-to-part variation may therefore be desirable.

[0034] As described below, an example process **200** is configured to produce transistors such as the transistor **100** in which the control electrode **130** and the field plate **150** are self-aligned.

Specifically, it will be understood that spacing between the control electrode **130** and the field plate **150** is determined by the spacing between the leftmost conductive element **135** and the field plate **150**. In addition, the location and dimensions of the first section **132** of the control electrode **130** is determined by the location and spacing of the conductive elements **135**. As described below, the process **200** includes forming these elements simultaneously.

[0035] FIGS. **2A-2E** illustrate example steps in the example process **200** for fabricating transistors with second electrodes operable as source-coupled field plates according to embodiments herein. The example process includes steps **210**, **220**, **230**, **240**, and **250**, which are depicted being performed to fabricate the transistor **100** of FIG. **1**. As above, the Figures, including FIGS. **2A-2E** are not necessarily to scale. It will be therefore be appreciated that certain elements of the process **200** are depicted in FIGS. **2A-2E** may omit certain details of relative dimensions and geometries of various elements. As one example, it will be appreciated that in many known lift-off processes, it is desirable for the photoresist thickness to exceed the thickness of the material being lifted off. However, for ease of illustration, the thickness of various sacrificial layers (e.g., the sacrificial materials **212**, **232**, **242**, **252**) may be depicted as being of similar thickness to the materials being lifted off. Similarly, angled and/or under-cut side-wall profiles are frequently desirable in lift-off process but such features may not be explicitly depicted.

[0036] At the outset of the process **200**, the substrate **102** is already provided the channel region **110**, the dielectric material **115** above the top surface **112** of the channel region **110**, and with the current terminals **120,125** as described in connection with FIG. **1**. In one or more embodiments, the dielectric thickness beneath the field plate **150** may be the dielectric material **115** may have a uniform thickness. In one or more other embodiments, suitable deposition and etch steps may be used to form the dielectric material **115** with different thicknesses in selected regions, while in one or more other embodiments, the dielectric material may be supplemented by another material (e.g., the dielectric material **417** described in connection with FIG. **4**, below).

[0037] At step **210**, depicted by FIG. **2A**, electrically conductive material is deposited and patterned on the substrate **102** using any suitable process. For example, as shown in FIG. **2A**, a sacrificial material **212** is patterned above the substrate **102** before the electrically conductive material is deposited. Undesired electrically conductive material **214** resting on the sacrificial material **212** is removed, leaving two conductive elements **135** and a third conductive element (the field plate **150**) behind, as seen in FIG. **2B**. As a non-limiting example, the sacrificial material may photolithographically patterned photoresist material. The photoresist is then stripped from the substrate **102** using a solvent, taking the undesired electrically conductive material **214** with it (a lift-off process). It will be appreciated that in other examples other suitable additive or subtractive processes may be used.

[0038] As another non-limiting example (not depicted), electrically conductive material may be deposited across the area shown, followed by lithographic patterning of an etch mask and etching of the electrically conductive material, except in the areas corresponding to the electrically conductive elements **135** and the field plate **150**. In one or more embodiments, conductive contacts (not shown) to the current terminals **120,125** may be simultaneously formed at step **210** from the

same electrically conductive material along with the electrically conductive elements **135** and the field plate **150**. Alternatively, a suitable conductive material may be deposited and selectively etched to form the electrically conductive elements **135** and field plate electrode **150**.

[0039] At step **220**, depicted by FIG. 2B, the dielectric material **140a** is deposited above the dielectric layer **115**, the electrically conductive elements **135**, and the field plate **150**, followed by deposition and patterning of sacrificial material **222** for use as an etch mask. As shown, the sacrificial material **222** is patterned to expose an area above and between the electrically conductive elements **135**. The dielectric material **140a** may then be etched using an etch process **224** to form an aperture in the region **226** indicated by dashed lines. The etch process **224** may be any suitable anisotropic process including, but not limited to dry plasma etching processes (e.g., sputter etching and/or reactive ion etching). The etch process **224** removes the exposed portions of the dielectric material **140a**, leaving an aperture that exposes the dielectric layer **115** above the channel region **110**. The electrically conductive material may be chosen at least in part for its resistance to the etch process **224** such that the etch process **224** etches the dielectric material **140a** at a significantly faster rate than it removes the electrically conductive material forming the electrically conductive elements **135** and the field plate **150**. In other words, the electrically conductive elements **135** and the field plate **150** serve as a hardmask during process **224** that defines the location and dimensions of the first section **132** of the control electrode **130**.

[0040] At step **230**, depicted by FIG. 2C, the control electrode **130** is formed in the aperture in the dielectric material **140a** formed at step **220**. As shown, the control electrode **130** is formed by a lift-off process in which sacrificial material **232** such as photoresist is deposited and patterned, following by deposition of electrically conductive material (e.g., a metal or metal alloy such as gold, copper, silver, etc.). However, it will be understood that any suitable additive or subtractive process may be used to form the control electrode **130**. It will be appreciated that the width and shape of the aperture in the dielectric material **140a** will be determined by the spacing of the electrically conductive elements **135** and the etch process **224** as performed during step **220**. For instance, the first end of the control electrode **130** will tend to have vertical sidewalls when a highly anisotropic etch is chosen for the etch process **224**, whereas if the etch process **224** is less highly anisotropic, the first section **132** of the control electrode **130** may have sloping sidewalls (e.g., as visible in the control electrode **430** depicted in FIG. 4A and FIG. 4B). The shape of the second end **134** of the control electrode will be determined at least in part by the width of the opening formed in the sacrificial material **232** (if a lift-off process is used) and the second end **134** may have vertical or sloping sidewalls, depending on the process parameters chosen. As shown, the control electrode **130** has a staggered T-shaped profile. In one or more embodiments, as shown, a portion of the dielectric material **140a** remains over the electrically conductive elements **135** and the field plate **150** and underneath the second section **134** of the control electrode **130**. In one or more other embodiments, the dielectric material **140a** may be removed. In other embodiments, portions of the dielectric material **140a** may be removed using an anisotropic etch process configured to leave portions of the dielectric material **140a** beneath the second section **134** of the control electrode **130** in place.

[0041] At step **240**, depicted by FIG. 2D, additional dielectric material **140b** is deposited above the control electrode **130**. As above, in one or more embodiments, the dielectric material **140b** is the same or similar to the dielectric material **140a**. Meanwhile, in one or more embodiments, the dielectric material **140b** is different from the dielectric material **140a**. As shown, sacrificial material **242** (e.g., photoresist or any other suitable material) is patterned above the dielectric material **140b** to serve as an etch mask for an etching process **244** which selectively removes the dielectric material **140** (i.e., the dielectric materials **140b**, **140a**) in the openings exposed in the regions **246**, **248**. In one or more embodiments (e.g., those in which the dielectric materials **140a**, **140b** are different from each other), the etch process may be a two-part etch process, in which a first etch is performed to selectively remove the dielectric material **140b** and a second etch is performed to

remove the dielectric material **140a**).

[0042] At step **250**, depicted by FIG. **2E**, sacrificial material **262** (e.g., photoresist) is patterned using any suitable process, followed by deposition of electrically conductive material. The conductive material may be deposited by any suitable process (e.g., thermal evaporation, sputtering, etc.). As shown, electrically conductive material fills the openings in the regions **246,248** formed at step **240** in order to form the interconnect **160** which electrically couples the field plate **150** to the current terminal **120** which may be operated as the source terminal of the transistor **100**. As depicted in FIG. **2E**, a lift-off process may be used to remove the sacrificial material **262** and the undesired electrically conductive material **264** with it, leaving only the interconnect **160** behind. It will be appreciated that while an additive process is depicted in FIG. **2E**, any suitable process, including a subtractive patterning process may be used to pattern the interconnect **160**.

[0043] It will be understood that dimensions of various features shown and described herein may be varied for to realize particular performance characteristics and other benefits. As an example, FIG. **3** is a cross-sectional schematic view of transistor **300** according to embodiments herein that is a variation of the example transistor **100**. Similarly to the transistor **100**, the transistor **300** is formed on a semiconductor substrate **302** (e.g., the substrate **102**). The transistor **300** has a channel region **310** (e.g., the channel region **110**) coupled to a current terminal **320** and a current terminal **325** (e.g., the current terminals **120,125**) with a first electrode (a control electrode **330** such as the electrode **130**) disposed between the two current terminals. The control electrode **330** has a first section **332** and a second section **334** (e.g., the first section **132** and the second section **134** of the electrode **130**). The first section **332** electrically contacts the channel region **310** within an aperture in the dielectric material **315** (e.g., the dielectric material **115**).

[0044] The transistor **300** also includes an electrode which is suitable for use a source-coupled field plate (a field plate **350**, such as the field plate **150**) and is electrically coupled to the current terminal **320** via an electrically conductive interconnect **360** (e.g., the interconnect **160**). Notably the gate electrode **330** has an asymmetrical profile wherein the second section **334** of the control electrode **330** extends towards the current terminal **320** (operable as a source terminal connected to the source-coupled field plate **350**). The asymmetrical profile of the control electrode **330** due to the laterally-extended portion **333** allows for additional electrically conductive material to form the control electrode **330**, thereby reducing gate resistance. Meanwhile, the material and thickness of the dielectric material **342a** can be chosen to mitigate additional C.sub.GS. Low gate resistance may provide increased power gain for RF power devices. Alternatively, longer gate fingers are possible for the same gain improving layout aspect ratio and reducing die area.

[0045] It will be understood that various materials may be chosen to form the features described above in one or more embodiments and these choices may be made for ease of manufacturing, for economic reasons, and/or to achieve particular performance characteristics. As an example, in one or more embodiments, the electrically conductive elements and the field plate may be formed from a first metal or metal alloy while the control electrode and the interconnect may be formed from a second metal or metal alloy. In one or more examples titanium, tungsten, or alloys thereof may be used as the first metal due to their suitability for use as etch masks and their adhesion properties, whereas the second metal may be a more highly conductive metal or metal alloy such as gold, silver, copper or alloys thereof. Moreover, conductive layers may be formed by stacks of different metals as convenient for processing or for achieving desired performance characteristics.

[0046] Similarly, the various dielectric layers of the transistors **100, 300** and other transistors described herein may be chosen to obtain desired performance characteristics including, but not limited to, particular values of C.sub.GD, C.sub.GS, and transistor threshold voltages. For instance, in one or more embodiments, the first dielectric layer and the second dielectric material (e.g., the dielectric material **115**, and the dielectric material **140**, and/or the dielectric materials **140a,140b**) are configured such the channel region (e.g., the channel region **110**) is fully depleted of free

charge carriers beneath the field plate electrode (e.g., the field plate electrode **150**) when an electrostatic potential difference between the field plate electrode and the channel region is between -2 Volts and -30 Volts.

[0047] In one or more embodiments having a laterally-extended control electrode such as the laterally-extended portion **333**, the various dielectric materials (e.g., the dielectric materials **315**, **340a**) are configured such that the summed capacitance per area between the electrically conductive elements (e.g., the conductive elements **335**) flanking the control electrode and the channel region (depicted by the respective capacitances $C1$ and $C2$ between the electrically conductive **335** and the channel region **310** in FIG. 3) is at least five times the capacitance per area between the laterally extended portion of the control electrode and the channel region depicted by $C3$ in FIG. 3. In other words, $(C1+C2) > (5 \times C3)$. Furthermore, in one or more embodiments, the capacitance per area between the electrically conductive elements (i.e., $C1+C2$ in FIG. 3) and the channel region is at least ten times greater than the capacitance per area between the control electrode and field plate interconnect above it, depicted by the capacitance $C4$ between the second portion **334** of the gate electrode **330** and the field plate interconnect **360**. In other words, $(C1+C2) > (10 \times C4)$.

[0048] In one or more embodiments, at least two different dielectric thicknesses separate a field plate (e.g., a field plate **150**, **350**) from the channel region (e.g., a channel region **110**, **310**). FIG. 4 is a schematic cross-sectional illustration one such embodiment. The transistor **400** has a channel region **410** that is electrically contacted on opposite ends by current terminals **420**, **425** on a substrate **402**. A control electrode **430** (e.g., the control electrode **130**) directly contacts the channel region **410**. Unlike the field plate **150** of the transistor **100**, the field plate **450** of the transistor **400** is separated from the channel region on the side nearest the control electrode **430** by the dielectric material **415** but is separated by both the dielectric material **415** and the additional dielectric material **417** on the side nearest the current terminal **425** which may be operated as the drain of the transistor **400**. In one or more embodiments, the dielectric material **417** is the same as the dielectric material **415**. For example, the dielectric material **415** may be deposited across the substrate **402** and then later patterned such that the dielectric material **417** is an area where dielectric material **415** has not been thinned. Alternatively, the dielectric material **417** may be formed by an additive process (e.g., a lift-off process) in which the dielectric material **417** is deposited above the previously-deposited dielectric material **415**. In one or more embodiments the dielectric material **417** is different from the dielectric material **415**.

[0049] As above, the example transistors **100**, **300** are represented schematically. FIG. 5A and FIG. 5B are schematic illustrations of an example transistor **500** in which various features of one or more embodiments are represented in greater detail and represented approximately to scale. The transistor **500** is fabricated on a substrate **502** (e.g., a substrate **102/302/402**) and has a channel region **510** (e.g., a channel region **110/310/410**) with a first dielectric layer **515** disposed above the channel region **510** (e.g., a channel region **110/310/410**). The transistor **500** has a first current terminal **520** (e.g., a current terminal **120/320/420**) and a second current terminal **525** (e.g., a current terminal **125/325/425**). The transistor **500** has a control electrode **530** with a noticeably more complex geometry than shown in FIGS. 1-4 that may result from the anisotropic deposition that results from a metal evaporation process. Also shown is the dielectric material **540** (e.g., dielectric material **140/340/440**) above the control electrode **530**, and the current terminals **520**, **525** and beneath a field plate interconnect **560** (e.g., a field plate interconnect **160/360/460**). Also shown is an electrically conductive contact **570** electrically coupled to the current terminal **525** and additional dielectric layers **580**, **590**.

[0050] FIG. 6 is a cross-sectional schematic illustration of an example control electrode **630** with an asymmetrical profile due to a laterally-extended portion **633** (e.g., the laterally-extended portion **333** of the control electrode **330**). The control electrode **630** is shown flanked by two conductive elements **635** (e.g., conductive elements **135/335/435/535**).

[0051] Features of embodiments may be understood by way of one or more of the following examples:

[0052] Example 1: A method of fabricating a semiconductor device that includes depositing first electrically conductive material over a first dielectric layer. The first dielectric layer overlies a channel region of a semiconductive substrate suitable for use as a semiconductive transistor channel. The method also includes, simultaneously forming, during a first patterning step, first, second, and third conductive elements above the channel region. The first, second, and third conductive elements are electrically isolated from each other and the second conductive element is disposed between the first conductive element and the third conductive element. The first, second, and third conductive elements are formed by selectively removing a portion of the first electrically conductive material.

[0053] The method of Example 1 also includes depositing second dielectric material over the first, second, and, third conductive elements, and over the first dielectric layer; and, during a second patterning step, forming a first aperture between the first and second conductive elements that passes through the first dielectric layer and the second dielectric material. The first aperture is formed by selectively removing a first portion of the second dielectric material to leave remaining second dielectric material; and removing a portion of the first dielectric layer above the channel region in an area between the first and second conductive elements.

[0054] The method of Example 1 also includes forming an electrically conductive control electrode; forming a second aperture that passes through the second dielectric material; and forming an electrically conductive field plate interconnect. The control electrode electrically contacts the first and second conductive elements and extends within the first aperture. The second aperture is formed during a third patterning step. The field plate interconnect extends within the second aperture and electrically contacts the third conductive element within the second aperture.

[0055] Example 2: A method as in Example 1 that further includes depositing additional dielectric material that overlies the control electrode and the remaining second dielectric material. In this example, forming the second aperture also includes selectively removing the additional dielectric material above the third conductive element to leave remaining additional dielectric material above the channel region and to leave the first and second conductive elements above the channel region.

[0056] Example 3: A method as in Example 2 that further includes causing a portion of the field plate interconnect to overlie the remaining additional dielectric material and the control electrode; and causing the field plate interconnect to electrically contact a first current terminal of the transistor at a first end of the channel region opposite the first, second, and third conductive elements that is nearest to the first conductive element.

[0057] Example 4: A method as in either of Examples 2 or 3, in which an effective dielectric constant of the additional dielectric material is lower than an effective dielectric constant of the first dielectric layer.

[0058] Example 5: A method as in any of Examples 1-4, in which forming the first aperture includes anisotropically etching the second dielectric material using a first anisotropic etching procedure. In this example, the first anisotropic etching process is characterized by a first etch rate with respect to the second dielectric material and a second etch rate with respect to the first electrically conductive material that is lower than the first etch rate.

[0059] Example 6: A method as in any of Examples 1-5, in which the first electrically conductive material is titanium, a titanium-tungsten alloy, or an aluminum-titanium alloy.

[0060] Example 7: A method as in any of Examples 2-6, in which forming the second aperture includes anisotropically etching the remaining second dielectric material and the remaining additional dielectric material using a second anisotropic etching procedure. In this example, the second anisotropic etching process is characterized by a third etch rate with respect to the additional dielectric material and a fourth etch rate with respect to the first electrically conductive material that is lower than the third etch rate.

[0061] Example 8: A method as in any of Examples 1-7, in which selectively removing a portion of the first electrically conductive material includes forming source and drain electrodes from the first electrically conductive material at opposite ends of the channel region simultaneously with forming the first, second, and third conductive elements.

[0062] Example 9A: A method as in any of Examples 1-8, in which the first dielectric layer has a thickness of less than 300 nanometers; and

[0063] Example 9: A method as in any of Examples 2-8, in which the first dielectric layer has a thickness of less than 300 nanometers. In this example, a cumulative thickness of the second dielectric material and the additional dielectric material is in a range from 50 to 5000 nanometers.

[0064] Example 10: A method as in any of Examples 1-9 that further includes forming a dielectric spacer above the first dielectric layer at a location between a first end and a second end of the channel region; and causing a portion of the third conductive element to overlie the dielectric spacer.

[0065] Example 11: A semiconductor device that includes a channel region defined in a semiconductor substrate, a first current terminal electrically coupled to a first end of the channel region, and a second current terminal electrically coupled to a second end of the channel region. The device of Example 11 has a first dielectric layer having a first dielectric thickness that overlies the channel region and a first aperture in the first dielectric layer that overlies the channel region. The device also includes an electrically conductive control electrode, an electrically conductive field plate electrode, and at least an electrically conductive first electrode extension. The device of Example 11 is configured to provide an electrically conductive path from the first current terminal to the second current terminal via the channel region when a sufficient control voltage is applied to the control electrode.

[0066] The control electrode extends within the first aperture and is configured to be electrically coupled to the channel region. The first electrode extension is adjacent to the first aperture, contacts a first side of the control electrode, and at least partially overlies the first dielectric layer. The first electrode extension and the field electrode are each formed from the same electrically conductive material.

[0067] Example 12: A semiconductor device as in Example 11 that further includes a dielectric spacer disposed between the first dielectric layer and a portion of the field plate electrode.

[0068] Example 13: A semiconductor device as in either of Examples 11 or 12 in which the channel region is formed by a two-dimensional electron gas (2DEG).

[0069] Example 14: A semiconductor device as in any of Examples 11-13, in which the channel region is formed by a 2DEG within a III-V semiconductor heterostructure.

[0070] Example 15: A semiconductor device as in any of Examples 11-14 that further include at least an electrically conductive second electrode extension adjacent to the first aperture. The second electrode extension at least partially overlies the first dielectric layer and contacts a second side of the control electrode that is opposite the first side of the control electrode. In this example, the second electrode extension is formed from the first electrically conductive material.

[0071] Example 16: A semiconductor device as in any of Examples 11-15, in which the control electrode is composed of first electrically conductive material and the first electrode extension is composed of second electrically conductive material that is different from the first electrically conductive material.

[0072] Example 17: A semiconductor device as in any of Examples 11-16 that further includes second dielectric material having a second dielectric thickness and overlying the first dielectric material; a second aperture through the second dielectric material above the field plate electrode; and an electrically conductive field plate interconnect that extends through the second aperture and is electrically coupled to the field plate electrode within the second aperture.

[0073] Example 18: A semiconductor device as in Example 17 in which additional dielectric material at least partially overlies the control electrode. In this example, the field plate interconnect

extends between the second electrode and the first current terminal and is configured to electrically couple the second electrode to the first current terminal. In this example, a portion of the field plate interconnect is disposed above the control electrode and is separated from the control electrode by the additional dielectric material.

[0074] Example 19: A semiconductor device as in any of Examples 17-18 in which a capacitance per area between the control electrode and the field plate interconnect is less than 10% of a capacitance per area between the first and second conductive elements and the channel region.

[0075] Example 20: A semiconductor device as in any of Examples 11-19 that further includes second dielectric material having a second dielectric thickness and overlying the first dielectric material. In this example, the second dielectric material overlies at least a first portion of the first electrode extension. In this example, a laterally-extended portion of the control electrode overhangs the first portion of the first electrode extension and is separated from the first portion of the first electrode extension by the second dielectric material.

[0076] Example 21: A semiconductor device as in any of Examples 11-20 in which a laterally-extended portion of the control electrode extends asymmetrically beyond the first electrode extension toward the first current terminal and is separated from the channel region by the second dielectric material and the first dielectric layer.

[0077] Example 22: A semiconductor device as in any of Examples 11-21 in which a capacitance per area between a laterally-extended portion of the control electrode and the transistor channel is less than 20% of a capacitance per area between the first and second conductive elements and the channel region.

[0078] Example 23: A semiconductor device as in any of Examples 11-22 in which the first dielectric layer and the second dielectric material are configured such the channel region is fully depleted of free charge carriers beneath the field plate electrode when an electrostatic potential difference between the field plate electrode and the channel region is in a range between -2 Volts and -30 Volts.

[0079] The preceding detailed description and examples are merely illustrative in nature and are not intended to limit the embodiments of the subject matter or the application and uses of such embodiments. As used herein, the word “exemplary” means “serving as an example, instance, or illustration.” Any implementation described herein as exemplary is not necessarily to be construed as preferred or advantageous over other implementations. Furthermore, there is no intention to be bound by any expressed or implied theory presented in the preceding technical field, background, or detailed description.

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[0081] It should be understood that this invention is not limited in its application to the details of construction and the arrangement of components set forth in the preceding description or illustrated in the accompanying drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways. Also, it is to be understood that the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of “including,” “comprising,” or “having” and variations thereof herein is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. Unless specified or limited otherwise, the terms “mounted,” “connected,” “supported,” and “coupled” and variations thereof are used broadly and encompass both direct and indirect mountings, connections, supports, and couplings. Further, “connected” and “coupled” are not restricted to physical or

mechanical connections or couplings.

[0082] The preceding discussion is presented to enable a person skilled in the art to make and use embodiments of the invention. Various modifications to the illustrated embodiments will be readily apparent to those skilled in the art, and the generic principles herein can be applied to other embodiments and applications without departing from embodiments of the invention. Thus, embodiments of the invention are not intended to be limited to embodiments shown, but are to be accorded the widest scope consistent with the principles and features disclosed herein. The preceding detailed description is to be read with reference to the figures, in which like elements in different figures have like reference numerals. The Figures, which are not necessarily to scale, depict selected embodiments and are not intended to limit the scope of embodiments of the invention. Skilled artisans will recognize the examples provided herein have many useful alternatives and fall within the scope of embodiments of the invention.

[0083] The connecting lines shown in the various figures contained herein are intended to represent exemplary functional relationships and/or physical couplings between the various elements. It should be noted that many alternative or additional functional relationships or physical connections may be present in one or more embodiments of the subject matter. In addition, certain terminology may also be used herein for the purpose of reference only, and thus are not intended to be limiting, and the terms “first,” “second” and other such numerical terms referring to structures do not imply a sequence or order unless clearly indicated by the context.

[0084] As used herein, a “node” or “terminal” means any internal or external reference point, connection point, junction, signal line, conductive element, or the like, at which a given signal, logic level, voltage, data pattern, current, or quantity is present. Furthermore, two or more nodes may be realized by one physical element (and two or more signals can be multiplexed, modulated, or otherwise distinguished even though received or output at a common node).

[0085] The foregoing description refers to elements or nodes or features being “connected” or “coupled” together. As used herein, unless expressly stated otherwise, “connected” means that one element is directly joined to (or directly communicates with) another element, and not necessarily mechanically. Likewise, unless expressly stated otherwise, “coupled” means that one element is directly or indirectly joined to (or directly or indirectly communicates with, electrically or otherwise) another element, and not necessarily mechanically. Thus, although the schematic shown in the figures depict one exemplary arrangement of elements, additional intervening elements, devices, features, or components may be present in one or more embodiments of the depicted subject matter.

Claims

1. A semiconductor device comprising: a channel region defined in a semiconductor substrate; a first current terminal electrically coupled to a first end of the channel region; a second current terminal electrically coupled to a second end of the channel region; a first dielectric layer having a first dielectric thickness and overlying the channel region; a first aperture in the first dielectric layer that overlies the channel region; an electrically conductive control electrode that extends within the first aperture that is configured to be electrically coupled to the channel region; at least an electrically conductive first electrode extension adjacent to the first aperture, the first electrode extension at least partially overlying the first dielectric layer and contacting a first side of the control electrode; and an electrically conductive field plate electrode above the channel region that is electrically coupled to the channel region, spaced apart from the first electrode extension, and overlies the first dielectric layer; wherein the first electrode extension and the field plate electrode are each formed from a first electrically conductive material; and wherein the device is configured to provide an electrically conductive path from the first current terminal to the second current terminal via the channel region when a sufficient control voltage is applied to the control electrode.

2. The semiconductor device of claim 1, further comprising a dielectric spacer disposed between the first dielectric layer and a portion of the field plate electrode.
 3. The semiconductor device of claim 1, wherein the channel region is formed by a two-dimensional electron gas (2DEG).
 4. The semiconductor device of claim 3, wherein the 2DEG is formed within a III-V semiconductor heterostructure.
 5. The semiconductor device of claim 1, further comprising: at least an electrically conductive second electrode extension adjacent to the first aperture, the second electrode extension at least partially overlying the first dielectric layer and contacting a second side of the control electrode that is opposite the first side of the control electrode; wherein the second electrode extension is formed from the first electrically conductive material.
 6. The semiconductor device of claim 1, wherein the control electrode is composed of first electrically conductive material and the first electrode extension is composed of a second electrically conductive material that is different from the first electrically conductive material.
 7. The semiconductor device of claim 1, further comprising: second dielectric material having a second dielectric thickness and overlying the first dielectric layer; a second aperture through the second dielectric material above the field plate electrode; and an electrically conductive field plate interconnect that extends through the second aperture and is electrically coupled to the field plate electrode within the second aperture.
 8. The semiconductor device of claim 7, wherein additional dielectric material at least partially overlies the control electrode; wherein the field plate interconnect extends between the field plate electrode and the first current terminal and is configured to electrically couple the field plate electrode to the first current terminal; and wherein a portion of the field plate interconnect is disposed above the control electrode and is separated from the control electrode by the additional dielectric material.
 9. The semiconductor device of claim 8, wherein a capacitance per area between the control electrode and the field plate interconnect is less than 10% of a capacitance per area between the first electrode extension and the channel region.
 10. The semiconductor device of claim 1, further comprising: second dielectric material having a second dielectric thickness and overlying the first dielectric layer; wherein the second dielectric material overlies at least a first portion of the first electrode extension; and wherein a laterally-extended portion of the control electrode overhangs the first portion of the first electrode extension and is separated from the first portion of the first electrode extension by the second dielectric material.
 11. The semiconductor device of claim 10, wherein the laterally-extended portion of the control electrode extends asymmetrically beyond the first electrode extension toward the first current terminal and is separated from the channel region by the second dielectric material and the first dielectric layer.
 12. The semiconductor device of claim 10, wherein a capacitance per area between the laterally-extended portion of the control electrode and the channel region is less than 20% of a capacitance per area between the first electrode extension and the channel region.
 13. The semiconductor device of claim 10, wherein the first dielectric layer and the second dielectric material are configured such that the channel region is fully depleted of free charge carriers beneath the field plate electrode when an electrostatic potential difference between the field plate electrode and the channel region is between -2 Volts and -30 Volts.
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