

FIELD EFFECT TRANSISTOR HAVING IMPROVED GATE STRUCTURES

TECHNICAL FIELD

[0001] This disclosure relates generally to Field Effect Transistors and more particularly to FETS having gate structures having low capacitance and resistance when such gate structures are in contact with, and connected, to copper Damascene based interconnects.

BACKGROUND OF THE INVENTION

[0002] As is known in the art, geometric scaling down in size of field effect transistor device dimension has a significant impact on high frequency performance. Typically when a transistor is scaled down in size, gate lengths are reduced along with source drain spacing. With this reduction in dimensions a greater emphasis is put on the placement of the gate within the source drain region with greatest potential performance enhancements achieved by placing the gate closer to the source than the drain. Also scaling of resistances can increase, in particular resistances of the gate, can adversely impact frequency response and noise figure of the transistor. Additionally dielectric loading in close proximity to gate electrode can also adversely impact transistor frequency response.

[0003] As is also known in the art, the manufacturing of GaN HEMT transistor devices and integrated circuits have been demonstrated in Silicon CMOS “like” single or dual damascene wafer processes (see “Towards a Si Foundry-Compatible, High-Performance, $\leq 0.25\mu\text{m}$ Gate, GaN-on-Si MMIC Process on High-Resistivity $\langle 111 \rangle$ Si With A Cu Damascene BEOL” by LaRoche et al., CS Man Tech Conference May 16th-19th, Miami, FL). This is possible due to compatibility of CMOS integrated processes and metallization schemes with GaN integrated circuited processes. To that end, as Gate Lengths of GaN HEMTs scale downward in size and dielectric loading is minimized when using CMOS “like” processes, as noted above, attention has to be giving to the gate size, placement, resistance and dielectric loading close to the gate.

[0004] In CMOS like processes, lithographic definition of fine line geometries of aggressively scaled FETs with conventional photolithography or electric beam (e-beam) lithography approaches can limit size, aspect ratio and placement of gates within source

drain regions. Sidewall image transfer techniques, where a thin film sidewall is defined about a sacrificial core or mandrel, are often used in used in nanometer CMOS processes. Additionally, with damascene interconnect in CMOS processes air-gaps about the metallization are often used to improve the frequency response of the passive interconnects, see for example “Multilevel Interconnect With Air-Gap Structure for Next-Generation Interconnections” Junji Noguchi et al., IEEE Transactions on Electron Devices Vol. 56, Issue 11, Nov 2009. However, the transistor itself is still dielectrically loaded by damascene oxide, degrading its frequency response.

SUMMARY OF THE INVENTION

[0005] In accordance with the present disclosure, a field effect transistor is provided having a gate contact and gate metal forming a vertical structure, such vertical structure having sides and a top surrounded by an air gap formed between a source electrode and a drain electrode of the field effect transistor.

[0006] In one embodiment, the source electrode and the drain electrode are damascene structures.

[0007] In one embodiment, the gate contact and gate metal form a vertical structure, such vertical structure having sides and a top surrounded by the air gap extending vertically to a level parallel to the top of the damascene structures.

[0008] In one embodiment, the gate contact is comprised of a plurality of stacked damascene metal layers.

[0009] In one embodiment, the gate contact is comprised of a plurality of stacked damascene metal layers extending vertically to a level parallel to a top of the damascene structures.

[0010] In one embodiment the field effect transistor is a mesa structure and wherein the gate contact and gate metal form a vertical structure, such vertical structure having sides and a top surrounded by an air gap formed between the source and drain electrodes and between the mesa edges that are perpendicular to the direction of the gate.

[0011] In one embodiment, a field effect transistor structure is provided, comprising: a III-N buffer layer; an III-N channel layer disposed over the III-N buffer layer; a barrier layer disposed on the channel layer; wherein a 2DEG is formed in the channel layer; a uniformly thick, horizontally extending doped GaN layer disposed on the III-N buffer layer, such uniformly thick layer of doped GaN having an aperture extending vertically there through, such aperture having vertically extending sidewalls terminating at horizontally extending upper surface portions of the III-N buffer layer; a gate electrode comprising: a vertical stem portion extending into the aperture, comprising: a portion of the III-N buffer layer, a portion of the III-N channel layer, and a portion of the buffer layer, such portion of the III-N buffer layer, the portion of the III-N channel layer, and the portion of the buffer layer forming a vertical stack of the portion of the III-N buffer layer, the portion of the III-N channel layer, and the portion of the buffer layer; wherein the vertical stack extends vertically upwardly into the aperture and between the vertically extending sidewalls of the aperture; and a gate metal disposed on the stack; source and drain contacts in Ohmic contact with an upper surface portions of the uniformly thick, horizontally extending layer of doped GaN; and wherein the gate electrode is disposed between the source and drain electrodes.

[0012] In one embodiment, a gate contact is disposed on the gate metal, and wherein the source and drain contacts have a lower portion; and wherein the gate contact and the lower portion of the source and drain contacts have upper surfaces disposed in a common plane.

[0013] In one embodiment, the source and drain electrodes are damascene structures.

[0014] In one embodiment, the gate contact and gate metal form a vertical structure, such vertical structure having sides and a top surrounded by an air gap extending vertically to a level parallel to a top of the damascene structures.

[0015] In one embodiment, the gate contact and gate metal form a vertical structure, such vertical structure having sides and a top surrounded by an air gap.

[0016] In one embodiment, the gate contact is comprised of a plurality of stacked damascene metal layers.

[0017] In one embodiment, the gate contact is comprised of a plurality of stacked damascene metal layers extending vertically to a level parallel to a top of the damascene structures.

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[0018] In one embodiment, the gate contact is comprised of a plurality of stacked damascene metal layers having non-conformal oxide disposed around the metal layers creating air gaps next to the metal layers extending vertically to a level parallel to a top of the damascene structures.

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[0019] In one embodiment, a method is provided for forming a field effect transistor, comprising: forming a mandrel on a surface of a semiconductor body; forming a first dielectric spacer layer having an inner sidewall on an outer sidewall of the mandrel and having a bottom on the semiconductor body; forming a gate electrode having an inner sidewall on an outer sidewall of the first dielectric spacer layer and having a bottom on the semiconductor body; forming a second dielectric layer having an inner sidewall on an outer sidewall of the gate electrode and having a bottom on the semiconductor body; wherein the first dielectric spacer layer has a different width than the second dielectric spacer layer; and, after having formed the first dielectric layer and the second dielectric layer, removing the mandrel while leaving the gate electrode with the bottom on the semiconductor;

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[0020] In one embodiment, a method is provided for forming a field effect transistor having a pair of electrically interconnected gate electrodes, one of the pair of gate electrodes being disposed between a first source electrode and a drain electrode and the other of the pair of gate electrodes being disposed between the drain electrode and a second source electrode, comprising: forming a mandrel on a surface of a semiconductor body; forming a first pair of dielectric spacer layers, each one having inner sidewalls on a corresponding one of a pair of opposing outer sidewalls of the mandrel; forming the pair of gate electrodes, one of the pair of gate electrodes being formed on outer sidewalls a first one of the first pair of dielectric spacer layers and another one of the pair of gate electrodes being formed on a second one of the first dielectric spacer layers; forming a second pair of dielectric spacer layers, each one having an inner sidewall on outer

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sidewalls of a corresponding one of the pair of the gate electrodes; wherein the first pair of dielectric spacer layers have different widths than the second pair of dielectric spacer layers; and after having formed the first pair dielectric layers and the second pair of dielectric layers, removing the mandrel.

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[0021] With such an arrangement, a self-aligned gate and regrown Ohmics utilizing the planar gate process and Cu Damascene structure provides more tightly controlled dimensions and the gate dielectric also acts as a spacer thereby improving access resistance by contacting to damascene metallization and gate aspect ratio. This approach allows us to achieve small source- drain gaps. High-yield manufacturability of this process is ensured by its completely subtractive nature versus lift-off based processing and the fact that the gate is stabilized in oxide until the air gap (which reduces parasitic capacitance to improve gain) is formed at the end of front end of line (FEoL) processing. The Cu Damascene with Self Aligned GAN HEMT, Planar, and adjacent HEMT Air Gap reduces capacitance.

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BRIEF DESCRIPTION OF THE DRAWINGS

[0022] FIGS. 1-6, 7C, 8-12, 12A, 13-14, 15A-15B, 16A, 16B, 17A, 17B, 18A-18I, are simplified, diagrammatical cross-sectional sketches of steps used in the formation of a Field Effect Transistor in accordance with the disclosure;

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[0023] FIGS. 4A, 5A, 6A, 7A, 7B, 8A, 13A, and 14A are simplified, diagrammatical plan view sketches of steps used in the formation of the Field Effect Transistor in accordance with the disclosure, FIGS. 4, 5, 6, 7C, 8, 13, 14, being taken along lines 4-4, 5-5, 6-6, 7C-7C, 8-8, 13-13, and 14-14, in FIGS. 4A, 5A, 6A, 7B, 8A, 13A, and 14A respectively;

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[0024] FIG. 19 is a simplified, diagrammatical plan view of the Field Effect Transistor in accordance with the disclosure, FIG. 19A being taken along line 19A-19A in FIG. 19;

[0025] FIG. 19B is a simplified, diagrammatical cross-sectional sketch of the Field Effect Transistor in accordance with the disclosure, FIG. 19B being taken along line 19B-19B in FIG. 19;

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[0026] FIG. 19A is a simplified, diagrammatical cross-sectional sketch of the Field Effect Transistor in accordance with an alternative embodiment of the disclosure;

[0027] FIGS. 20A – 20F, 20J-20W are simplified, diagrammatical cross-sectional sketches of steps used in the formation of a Field Effect Transistor in accordance with a second alternative embodiment of the disclosure;

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[0028] FIGS. 20G, 20H, 20I, and 20X are simplified, diagrammatical plan views of the Field Effect Transistor in accordance with the second alternative embodiment of the disclosure at various stages in the fabrication thereof; FIGS. 20F, 20J and FIG. 20W being taken along lines 20F-20F, 20J-20J and 20W-20W, in FIGS. 20G, 20I and 20X, respectively;

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[0029] FIG. 20X is a simplified, diagrammatical plan view of formation of the Field Effect Transistor FIG. 20W; and

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[0030] FIG. 21 is a simplified, diagrammatical cross-sectional sketch of the Field Effect Transistor in accordance with an alternative embodiment of the disclosure.

[0031] Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

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[0032] Referring now to FIG. 1, a substrate 10, here for example silicon (Si) or silicon carbide, is shown having a Group III-V layer, here an aluminum Nitride (AlN), Gallium Nitride (GaN) or combination thereof nucleation layer or buffer/back barrier layer 12 formed epitaxially on the upper surface of the substrate 10, an undoped Group III-V layer 14, here a Gallium Nitride (GaN) layer 14 formed epitaxially on the upper surface of the layer 12 and a Group III-V layer 16, here AlGaN layer 16 formed epitaxially of the upper surface of the GaN layer 14, the GaN layer 14 providing a carrier channel, as indicated.

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[0033] Referring to FIG. 2, a silicon oxide layer 18 is formed on the upper surface of the layer 14, as shown.

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[0034] Referring now to FIG. 3, isolation regions 20 are formed through portions of the silicon dioxide layer 18, AlGaIn layer 16, GaN layer 14 and into the upper portion of buffer layer 12, as shown; here, for example, such isolation regions 20 are formed by oxygen ion implantation. It should be understood that layers could be etched to form a conventional mesa isolation type structure.

[0035] Referring now to FIGS. 4 and 4A, a sacrificial hard mask 22, here a four sided, rectangular-shaped, mandrel, or core, here for example polysilicon, silicon nitride, aluminum oxide, amorphous carbon or other suitable hard mask material, is formed as shown on a portion of the upper surface of the silicon oxide layer 18 in any conventional manner.

[0036] Referring now to FIGS. 5 and 5A, a conformal dielectric spacer layer 24, here Aluminum Oxide (Al₂O₃) polysilicon, silicon nitride, silicon oxide, amorphous carbon or other suitable material is deposited over the entire upper surface of the structure shown in FIG. 4, here by, for example, Chemical Vapor Deposition (CVD), sputter or Atomic Layer Deposition (ALD).

[0037] Referring to FIGS. 6 and 6A, portions of the dielectric spacer layer 24 are removed from the upper surface of the mandrel 22 and upper surface portions of the oxide layer 18 using a directional etch by plasma, Inductive Coupled Plasma (ICP) etch or Reactive Ion Etch (RIE) to produce the structure as shown

[0038] Referring to FIGS. 7A, the mandrel 22 is removed by selective wet or dry etching and then a trim masking lithographic process is used to remove a pair of opposing dielectric spacer layer 24B while leaving the other pair of opposing dielectric spacer layer 24A, as shown in FIGS. 7A, 7B and 7C.

[0039] Referring to FIGS. 8 and 8A, the exposed portions silicon oxide layer 18 are removed, here for example by plasma etching exposing the top portion of the GaN epitaxial layer 14; it being noted that the portion of the silicon oxide layer 18 under the of the dielectric spacer layer 24 remain, as shown.

[0040] Referring now to FIG. 9, portions of the then expose portions of the AlGa_N layer 16 are removed followed by removal of the then exposed portion of the Ga_N layer 14, followed by removal of the then exposed upper portions of the Al_N layer 12; here by selective wet or dry etching; it being noted that the portions of the AlGa_N layer 16, portions of the Ga_N layer 14 and portions of the Al_N layer 12 under the dielectric spacer layer 12, as well as portions of the isolation regions 20 remain, as shown.

[0041] Referring now to FIG. 10, a layer 30 of N⁺⁺ doped of Ga_N; a so-called regrown layer, is formed over the exposed portions of the Al_N layer 12 and with portions 30A being deposited over the dielectric spacer layer 24, as shown using molecular beam epitaxy or Metal-Organic Chemical Vapor Deposition (MOCVD).

[0042] Referring now to FIG. 11, a wet or dry selective poly-crystalline Ga_N etch is use to remove the portion deposited over the dielectric spacer layer 24 resulting in the structure shown in FIG. 12.

[0043] Referring to FIG. 12A, a photoresist layer 32 is formed over a portion of the structure for the purpose of exposing a portion 30 of the N⁺⁺ regrown Ohmics layer 30; it being noted that the photoresist layer 32 has ends thereof extending over a portion of the implanted regions 20, as shown in FIG. 12A. A suitable wet or plasma etching process, is used to etch and remove exposed portions 30 of the Regrown Ohmics layer 30, FIGS. 13 and 13A. The then exposed portions of dielectric spacer layer 24 and the photoresist layer 32 is removed resulting in structure shown in FIGS. 14 and 14A.

[0044] Referring to FIG. 15A, a thin dielectric layer 38, here for example, Si₃N₄, is formed over the surface and then chemical mechanical polished exposing the upper portions of silicon dioxide layer 18 are exposed, as shown in 15B.

[0045] Referring to FIG. 16, the exposed portions of silicon dioxide layer 18 are removed by selective wet or dry etching thereby exposing underlying portions of the AlGa_N layer 16, as shown.

[0046] Referring to FIG 16A, a dielectric liner material 70A, for example Si₃N₄ or Al₂O₃, is first conformally deposited over the structure and then directionally etched as shown in

FIG. 16B, leaving portions 70B of the dielectric liner layer on the sidewalls of the regrown Ohmic layer 30 and on the gate opening, as shown in FIG. 16B.

[0047] Referring now to FIG. 17A, a gate metal layer 42a, for example a lower layer of Titanium Nitride (TiN) and upper layer of Tungsten (W), is sputter deposited over the structure, as shown. A photoresist mask 46 is used with a dry etch, to pattern layer 42a into a pair of Schottky gate metal contact 42a, 42b, as shown in FIG. 17B.

[0048] Referring now to FIGS. 18A-18I, a process is described to form a pair of source contacts 50S and a drain contact 50D (FIG. 18D, I) as damascene structures, here, for example, Damascene structures, in ohmic contact with N⁺⁺ regrown Ohmics layer 30. Thus, referring to FIG. 18A, an additional silicon nitride (SiN_x) stop etch layer 47a is deposited over SiN_x layer 38 and over the pair of Schottky gate metal contacts 42a and 42b as shown in FIG. 18A.

[0049] Referring to FIG. 18B, a dielectric layer 48a, here for example, silicon dioxide, is deposited by chemical vapor deposition (CVD) over SiN_x layer 47a, planarized by Chemical Mechanical Planarization (CMP), and photo-lithographically pattern and etched to first form a pair of windows 48WG1 and 48WG2 for the gate contacts 42a, 42b (FIG. 18B) and then windows 48WS1, 48WS2, 48WD, for the pair of source contacts 50S and drain contact 50D (FIG. 18D, 18I). The exposed portions of the SiN_x layer 47 are removed to form windows 50₁, 50₂ (FIG. 18C), to expose the gate and portions of the N⁺⁺ regrown Ohmics layer 30 where the pair of source contacts 50S, a drain contact 50D, and two gate contacts 50G are to be formed by an additional plating and chemical mechanical polish (CMP) of Metal layer V_O (here copper) in windows 50₁, 50₂, as shown in FIG. 18D.

[0050] Referring to FIG. 18E, in a similar manner a dielectric layer 47b, here for example, silicon nitride followed by a layer 44b of silicon dioxide are deposited; windows, not shown, are formed therein and upper metal layers M1, here copper, are deposited through the windows onto metal layers V_O, as shown; followed by another layer 47c of silicon nitride, as shown in FIG. 18E to form damascene structures 49S₁, 49D₁ in contact with lower part of the source and drain contact, S and D, respectively, (FIG. 18H).

[0051] The process repeats, as shown in FIGS. 18G and 18H, to form damascene structures 49S₂, 49D₂ for the upper part of the source and drain contact, S and D, respectively, FIG. 18H.

5 [0052] Next, air gaps 60 are etched into the structure using conventional photolithographic etching techniques to form the structure shown in FIG. 18I.

[0053] As noted above, here the source and drain contacts 50S and 50D (FIG. 18I) are formed as damascene structures dielectric layers of SiN_x and SiO are formed as shown in
10 FIG. 18I to provide upper, here copper (Cu) contact metal layers V0, M1, V1, and M2 to the source and drain electrodes 50S and 50D, and gate contacts 42a, 42b (FIG. 18B) as shown in FIG. 18I.

[0054] Referring to FIGS. 19, 19A and 19B an alternative damascene structure with non-conformal damascene oxide that creates air pockets 51 is formed for the source and drain
15 electrodes 50S and 50D.

[0055] Referring now to FIGS. 20A-20V, an alternative embodiment will be described. Here the separation between the gate electrode and the source electrode will be different
20 from the separation between the gate electrode and the drain electrode; a so-called asymmetrical gate FET gate structure.

[0056] Thus, here, after the mandrel 22 is formed as described above in FIG. 4, layer 24₁ having a uniform thickness of W1 is formed over the surface of the structure shown in
25 FIG. 4, here for example Al₂O₃, SiO₂, SiN, polycrystalline silicon or an Amorphous Carbon layer deposited by CVD, ALD, sputter to produce the structure shown in FIG. 20A.

[0057] Referring to FIG. 20B, the portions of layer 24₁ are removed as shown using for
30 example directional etch by plasma, ICP or RIE. Mandrel, and spacer material plus etch conditions chosen to provide good dry etch selectivity to produce the structure shown in FIG. 20B. It is noted that portion of layer 24₁ remain on the vertical sidewalls of the mandrel 22, as shown.

[0058] Referring to FIG. 20C, a layer 24₂ is deposited over the structure as shown. Here, layer 24₂ is: Al₂O₃, SiO₂, SiN, polycrystalline silicon, Amorphous Carbon layer or other suitable material is deposited by CVD, ALD, or sputtering.

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[0059] Referring to FIG. 20D, the portions of layer 24₂ are removed as shown using for example directional etch by plasma, ICP or RIE to produce the structure shown in FIG. 20D. It is noted that portion of layer 24₂ remain on the vertical sidewalls of the layer 24₁ which are, as described above, on the vertical sidewalls of the mandrel 22, as shown.

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[0060] Referring to FIG. 20E, a layer 24₃ is deposited uniformly, here having a thickness W₂, where W₂ is different from W₁ over the structure as shown. Here, layer 24₃ is: Al₂O₃, SiO₂, SiN, polycrystalline silicon, Amorphous Carbon layer, or other suitable material deposited by CVD, ALD, or sputtering.

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[0061] Referring to FIGS. 20F and 20G, the portions of layer 24₃ are removed as shown using for example directional etch by plasma, ICP or RIE to produce the structure shown in FIG. 20F. It is noted that portion of layer 24₃ remain on the vertical sidewalls of the layer 24₂, as shown.

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[0062] Referring to FIG. 20H – FIG. 20J the mandrel 22 is removed as described in connection with FIG. 7A by selective wet or dry etching and then a trim masking lithographic process is used to remove the pairs of opposing layer 24₁, 24₂ and 24₃ while leaving the other pair of opposing layers 24₁, 24₂ and 24₃ as described in connection with FIGS. 7B and 7C to produce the structure shown in FIGS. 20I and 20J.

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[0063] Referring to FIG. 20K, the exposed portions of the oxide layer 18 are removed as described above in connection with FIG. 8.

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[0064] Referring to FIG. 20L, exposed portions of layer 16 and 14 are removed as described above in connection with FIG. 9.

[0065] Referring to FIG. 20M, a layer 30 of N⁺⁺ GaN is deposited over the structure as shown by MBE, MOCVD as described above in connection with FIG. 10.

5 [0066] Referring to FIG. 20N, portion on the layer 30 on the upper surface of layers 22₁, 22₂, and 22₃ are removed by selective dry or wet etch, as described in FIG 12

[0067] Referring to FIG. 20O, a photoresist layer 32 is formed over a portion of the structure for the purpose of exposing portion 30A of the N⁺⁺ regrown Ohmics layer 30; it being noted that the photoresist layer 32 has ends thereof extending over a portion of the
10 implanted regions 30, as described above in FIG. 12A. An etching process is then used to form the mesa structure 35, as described above in FIGS. 14 and 14A, after the mask 34 has been removed, as shown in FIG. 20P.

[0068] Referring to FIGS. 20Q a dielectric layer 38, here for example, SiN_x, is formed
15 over the surface and then chemical mechanical polished, as shown in FIG. 20R exposing upper surfaces of layers 24₁, 24₂ and 24₃, as shown

[0069] Referring to FIG. 20S, the surface of the structure is masked with windows to exposed portions of the indicated by arrows 39, and then such exposed portions are
20 subjected to a dry, selective etch to remove layer 24₂, and thereby exposing underling portions of oxide layer 18, such exposed portions of layer 18 then being removed by a plasma etch or ICP or RIE to produce the structure to expose underlying portions of layer 16 as shown in FIG. 20S.

[0070] Referring to FIG. 20T gate metal layer structure 44, for example a lower layer of
25 Titanium Nitride (TiN) and upper layer of Tungsten (W) is blanket deposited over the structure, as shown.

[0071] Referring to FIG. 20U, a photoresist a mask 46 is used with a dry etch, to pattern layer 44 into a pair of Schottky gate metal contact 44a, 44b, as shown and as described in
30 connection with FIG. 17B and as shown in FIGS. 20V .

[0072] Referring to FIG. 20W a silicon nitride (SiN_x) etch stop layer 47 is deposited over SiN_x layer 38 and over the pair of Schottky gate metal contact 44a, 44b, as described FIG. 18A. The process then continues as described in the FIGS. 18B through 18I

5 [0073] It should be understood that in order to lower gate resistance, and thereby improve frequency response, here for example additional Cu Damascene metal layers M1 and V1 and M2 are stacked above the V0 gate Cu Damascene layer V0 in contact with the gate metal layer 42a, 42b. It should be understood that more or less Cu Damascene layers may be stacked above the V0 Gate. The cross section, as shown in FIG 21, is formed as
10 previously described above.

[0074] It should now be appreciated, a field effect transistor according to the disclosure includes a gate contact and gate metal forming a vertical structure, such vertical structure having sides and a top surrounded by an air gap formed between a source electrode and a
15 drain electrode of the field effect transistor. The field effect transistor may include, either individually or in combination, one or more of the following features to include: wherein the source electrode and the drain electrode are damascene structures; wherein the gate contact and gate metal form a vertical structure, such vertical structure having sides and a top surrounded by the air gap extending vertically to a level parallel to a top of the
20 damascene structures; wherein the gate contact is comprised of a plurality of stacked damascene metal layers; wherein the gate contact is comprised of a plurality of stacked damascene metal layers extending vertically to a level parallel to tops of the damascene structures; or wherein the field effect transistor is a mesa structure and wherein the gate contact and gate metal form a vertical structure, such vertical structure having sides and a
25 top surrounded by an air gap formed between the source and drain electrodes and between edges of the mesa structure are perpendicular to the direction of the gate.

[0075] It should now also be appreciated, a field effect transistor structure according to the disclosure includes: a III-N buffer layer; an III-N channel layer disposed over III-N
30 buffer layer; a barrier layer disposed on the channel layer; wherein a 2DEG is formed in the channel layer; a uniformly thick, horizontally extending doped GaN layer disposed on the III-N buffer layer, such uniformly thick layer of doped GaN having an aperture extending vertically there through, such aperture having vertically extending sidewalls

terminating at horizontally extending upper surface portions of the III-N buffer layer; a gate electrode comprising: a vertical stem portion extending into the aperture, comprising: a portion of the III-N buffer layer, a portion of the III-N channel layer, and a portion of the buffer layer, such portion of the III-N buffer layer, the portion of the III-N channel layer, and the portion of the buffer layer forming a vertical stack of the portion of the III-N buffer layer, the portion of the III-N channel layer, and the portion of the buffer layer; wherein the vertical stack extends vertically upwardly into the aperture and between the vertically extending sidewalls of the aperture; and a gate metal disposed on the stack; source and drain contacts in Ohmic contact with an upper surface portions of the uniformly thick, horizontally extending layer of doped GaN; and wherein the gate electrode is disposed between the source and drain electrodes. The field effect transistor structure may include, either individually or in combination, one or more of the following features to include: a gate contact disposed on the gate metal, and wherein the source and drain contacts have a lower portion; and wherein the gate contact and the lower portion of the source and drain contacts have upper surfaces disposed in a common plane; wherein the source and drain electrodes are damascene structures; wherein the gate contact and gate metal form a vertical structure, such vertical structure having sides and a top surrounded by an air gap extending vertically to a level parallel to tops of the damascene structures; wherein the gate contact and gate metal form a vertical structure, such vertical structure having sides and a top surrounded by an air gap; wherein the gate contact is comprised of a plurality of stacked damascene metal layers; or wherein the gate contact is comprised of a plurality of stacked damascene metal layers extending vertically to a level parallel to a top of the damascene structures.

[0076] It should now also be appreciated, a method for forming a field effect transistor according to the disclosure includes: forming a mandrel on a surface of a semiconductor body; forming a first dielectric spacer layer having an inner sidewall on an outer sidewall of the mandrel and having a bottom on the semiconductor body; forming a gate electrode having an inner sidewall on an outer sidewall of the first dielectric spacer layer and having a bottom on the semiconductor body; forming a second dielectric layer having an inner sidewall on an outer sidewall of the gate electrode and having a bottom on the semiconductor body; wherein the first dielectric spacer layer has a different width than the second dielectric spacer layer; and, after having formed the first dielectric layer and the

second dielectric layer, removing the mandrel while leaving the gate electrode with the bottom on the semiconductor body.

5 [0077] It should now also be appreciated, a method for forming a field effect transistor having a pair of electrically interconnected gate electrodes, one of the pair of gate electrodes being disposed between a first source electrode and a drain electrode and the other of the pair of gate electrodes being disposed between the drain electrode and a second source electrode according to the disclosure includes: forming a mandrel on a surface of a semiconductor body; forming a first pair of dielectric spacer layers, each one
10 having inner sidewalls on a corresponding one of a pair of opposing outer sidewalls of the mandrel; forming the pair of gate electrodes, one of the pair of gate electrodes being formed on outer sidewalls a first one of the first pair of dielectric spacer layers and another one of the pair of gate electrodes being formed on a second one of the first dielectric spacer layers; forming a second pair of dielectric spacer layers, each one having an inner
15 sidewall on outer sidewalls of a corresponding one of the pair of the gate electrodes; wherein the first pair of dielectric spacer layers have different widths than the second pair of dielectric spacer layers; after having formed the first pair dielectric layers and the second pair of dielectric layers, removing the mandrel.

20 [0078] A number of embodiments of the disclosure have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the disclosure. Accordingly, other embodiments are within the scope of the following claims.

WHAT IS CLAIMED IS:

1. A field effect transistor, comprising a gate contact and gate metal forming a vertical structure, such vertical structure having sides and a top surrounded by an air gap
5 formed between a source electrode and a drain electrode of the field effect transistor.
2. The field effect transistor recited in claim 1 wherein the source electrode and the drain electrode are damascene structures.
- 10 3. The field effect transistor recited in claim 2 wherein the gate contact and gate metal form a vertical structure, such vertical structure having sides and a top surrounded by the air gap extending vertically to a level parallel to a top of the damascene structures.
4. The field effect transistor recited in claim 3 wherein the gate contact is
15 comprised of a plurality of stacked damascene metal layers.
5. The field effect transistor recited in claim 4 wherein the gate contact is comprised of a plurality of stacked damascene metal layers extending vertically to a level parallel to tops of the damascene structures.
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6. The field effect transistor recited in claim 5 wherein the field effect transistor is a mesa structure and wherein the gate contact and gate metal form a vertical structure, such vertical structure having sides and a top surrounded by an air gap formed between the source and drain electrodes and between edges of the mesa structure are perpendicular to
25 the direction of the gate.
7. A field effect transistor structure, comprising:
 - a III-N buffer layer;
 - an III-N channel layer disposed over III-N buffer layer;
 - 30 a barrier layer disposed on the channel layer;
 - wherein a 2DEG is formed in the channel layer;
 - a uniformly thick, horizontally extending doped GaN layer disposed on the III-N buffer layer, such uniformly thick layer of doped GaN having an aperture extending vertically there through, such aperture having vertically extending

sidewalls terminating at horizontally extending upper surface portions of the III-N buffer layer;

a gate electrode comprising:

a vertical stem portion extending into the aperture, comprising:

5 a portion of the III-N buffer layer, a portion of the III-N channel layer, and a portion of the buffer layer, such portion of the III-N buffer layer, the portion of the III-N channel layer, and the portion of the buffer layer forming a vertical stack of the portion of the III-N buffer layer, the portion of the III-N channel layer, and the portion of the buffer layer;

10 wherein the vertical stack extends vertically upwardly into the aperture and between the vertically extending sidewalls of the aperture; and

a gate metal disposed on the stack;

source and drain contacts in Ohmic contact with an upper surface portions of the uniformly thick, horizontally extending layer of doped GaN; and

15 wherein the gate electrode is disposed between the source and drain electrodes.

8. The field effect transistor structure recited in claim 7 including:

20 a gate contact disposed on the gate metal, and wherein the source and drain contacts have a lower portion; and wherein the gate contact and the lower portion of the source and drain contacts have upper surfaces disposed in a common plane.

9. The field effect transistor structure recited in claim 8 wherein the source and drain electrodes are damascene structures.

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10. The field effect transistor structure recited in claim 9 wherein the gate contact and gate metal form a vertical structure, such vertical structure having sides and a top surrounded by an air gap extending vertically to a level parallel to tops of the damascene structures.

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11. The field effect transistor structure recited in claim 7 wherein the gate contact and gate metal form a vertical structure, such vertical structure having sides and a top surrounded by an air gap.

12. The field effect transistor structure recited in claim 10 wherein the gate contact is comprised of a plurality of stacked damascene metal layers.

5 13. The field effect transistor structure recited in claim 12 wherein the gate contact is comprised of a plurality of stacked damascene metal layers extending vertically to a level parallel to a top of the damascene structures.

10 14. A method for forming a field effect transistor, comprising:
 forming a mandrel on a surface of a semiconductor body;
 forming a first dielectric spacer layer having an inner sidewall on an outer
 sidewall of the mandrel and having a bottom on the semiconductor body;
 forming a gate electrode having an inner sidewall on an outer sidewall of
 the first dielectric spacer layer and having a bottom on the semiconductor body;
15 forming a second dielectric layer having an inner sidewall on an outer
 sidewall of the gate electrode and having a bottom on the semiconductor body;
 wherein the first dielectric spacer layer has a different width than
 the second dielectric spacer layer; and,
 after having formed the first dielectric layer and the second dielectric layer,
20 removing the mandrel while leaving the gate electrode with the bottom on the
 semiconductor body.

25 15. A method for forming a field effect transistor having a pair of electrically
interconnected gate electrodes, one of the pair of gate electrodes being disposed between a
first source electrode and a drain electrode and the other of the pair of gate electrodes
being disposed between the drain electrode and a second source electrode, comprising:
 forming a mandrel on a surface of a semiconductor body;
 forming a first pair of dielectric spacer layers, each one having inner sidewalls on
 a corresponding one of a pair of opposing outer sidewalls of the mandrel;
30 forming the pair of gate electrodes, one of the pair of gate electrodes being formed
on outer sidewalls a first one of the first pair of dielectric spacer layers and another one of
the pair of gate electrodes being formed on a second one of the first dielectric spacer
layers;

forming a second pair of dielectric spacer layers, each one having an inner sidewall on outer sidewalls of a corresponding one of the pair of the gate electrodes;

wherein the first pair of dielectric spacer layers have different widths than the second pair of dielectric spacer layers;

5 after having formed the first pair dielectric layers and the second pair of dielectric layers, removing the mandrel.