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(54) **INTEGRATION OF ELECTRONICS WITH LITHIUM NIOBATE PHOTONICS**

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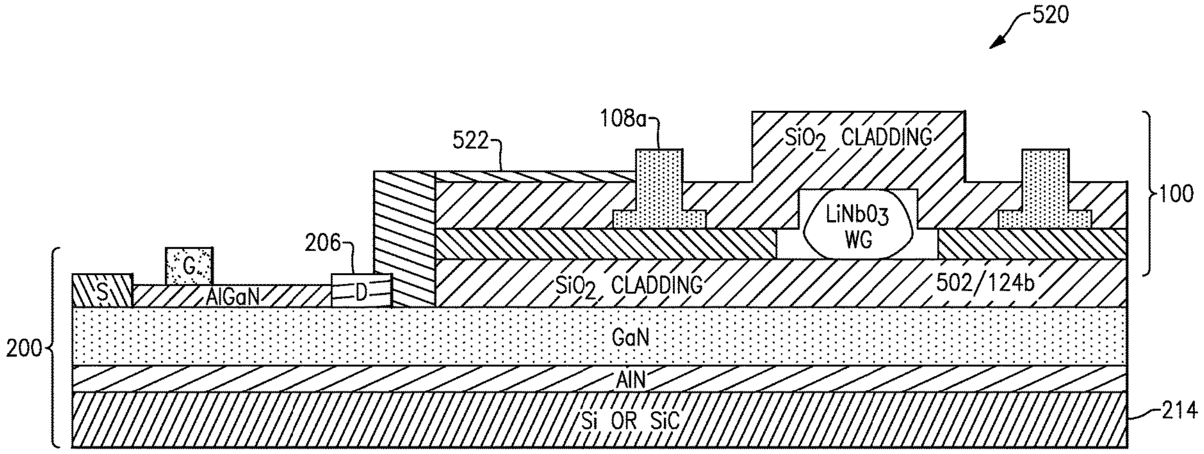
(57) **ABSTRACT**

An electro-optical modulator assembly including a transistor including a gate, a drain, a source, and a film forming a channel layer for the transistor disposed on a substrate, a photonic modulator including a first waveguide structure positioned between a first electrode and a second electrode, the photonic modulator including a portion disposed over a portion of the transistor, and a metal connection coupled between the drain of the transistor and one of the first and second electrodes of the photonic modulator.



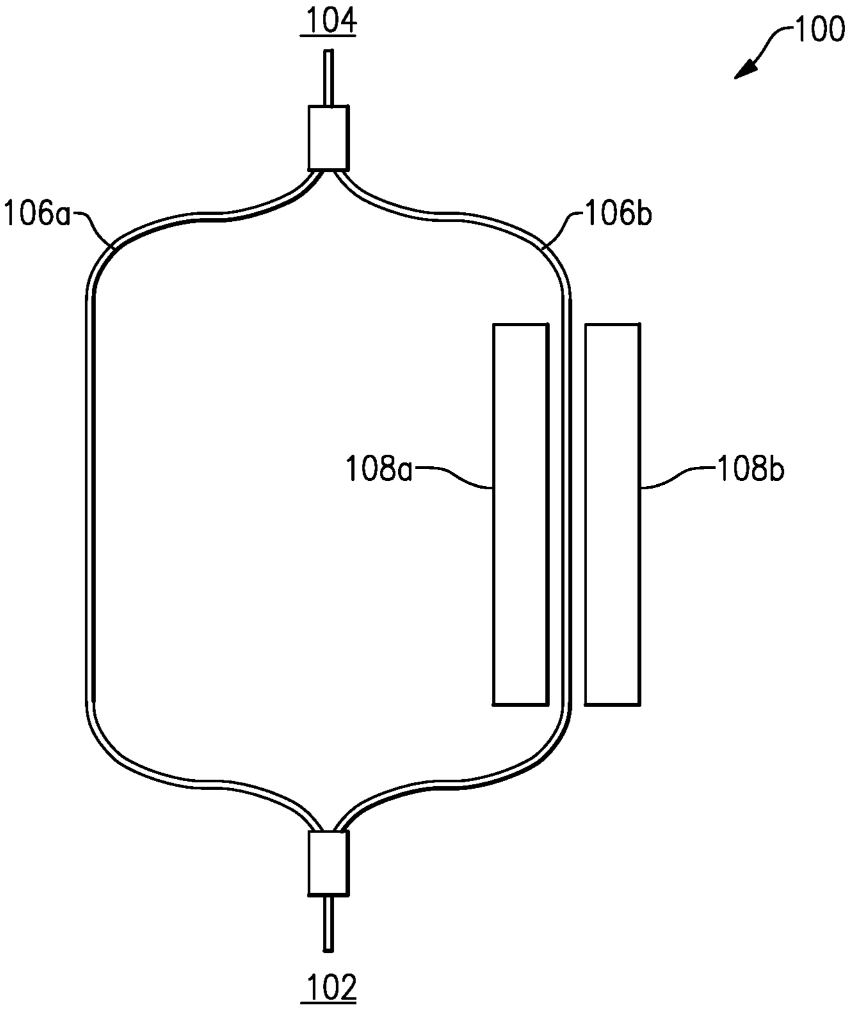


FIG.1A

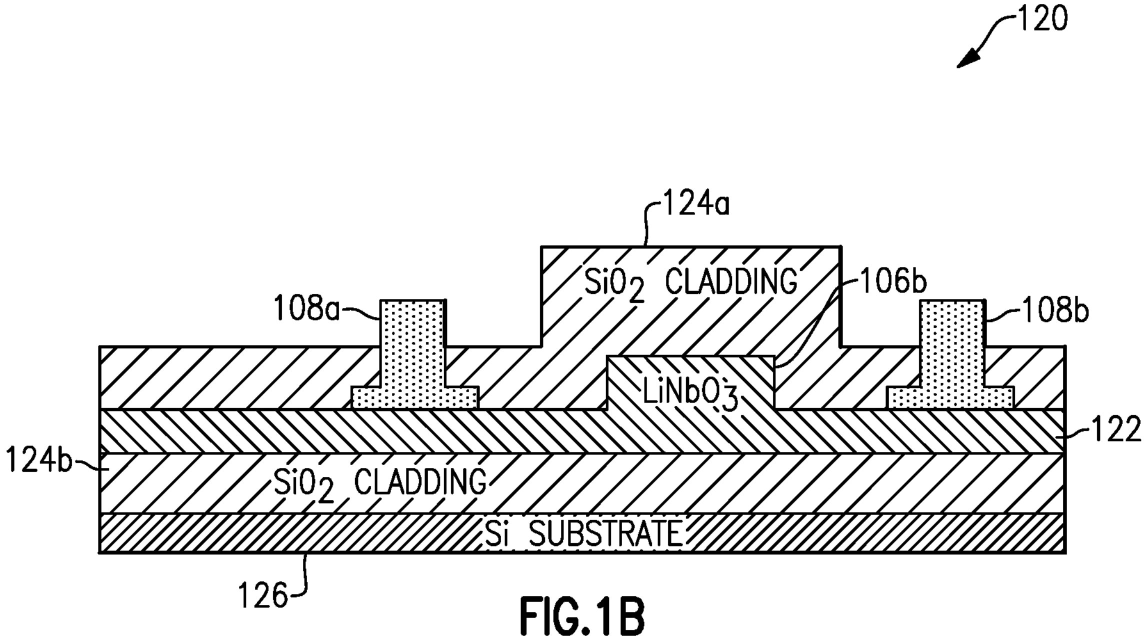

120
124a
SiO$_2$ CLADDING
106b
108a
108b
LiNbO$_3$
122
124b
SiO$_2$ CLADDING
Si SUBSTRATE
126

FIG.1B

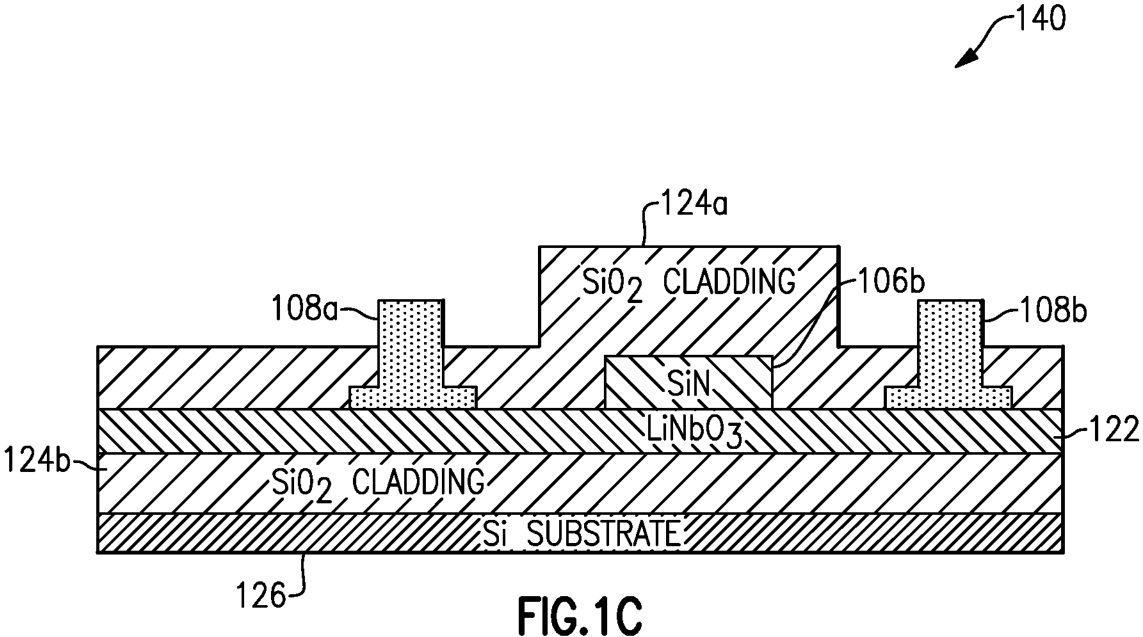

140
124a
SiO$_2$ CLADDING
106b
108a
108b
SiN
LiNbO$_3$
122
124b
SiO$_2$ CLADDING
Si SUBSTRATE
126

FIG.1C

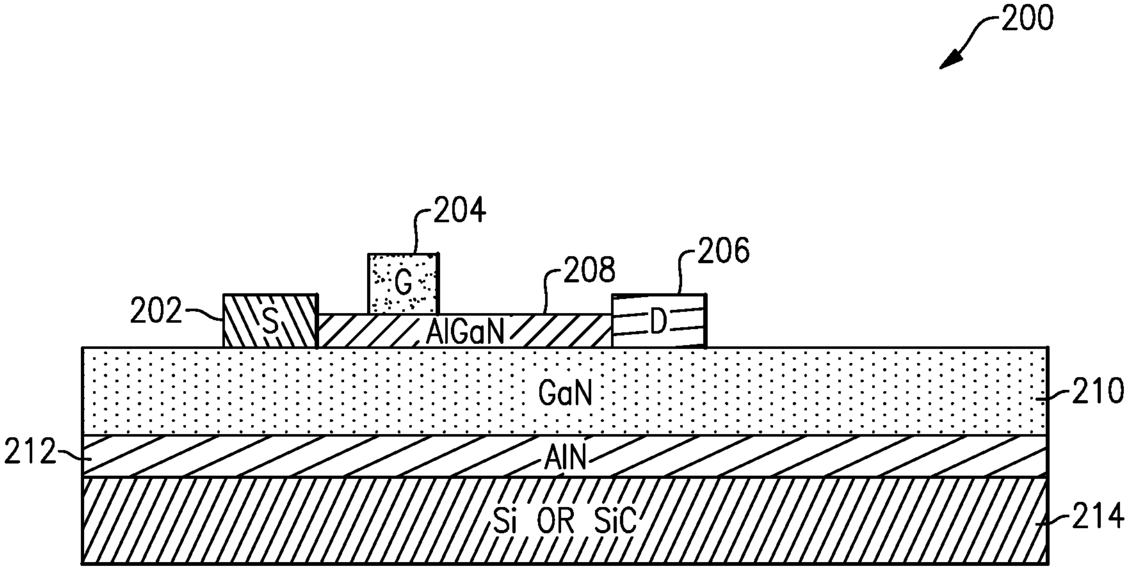


FIG.2

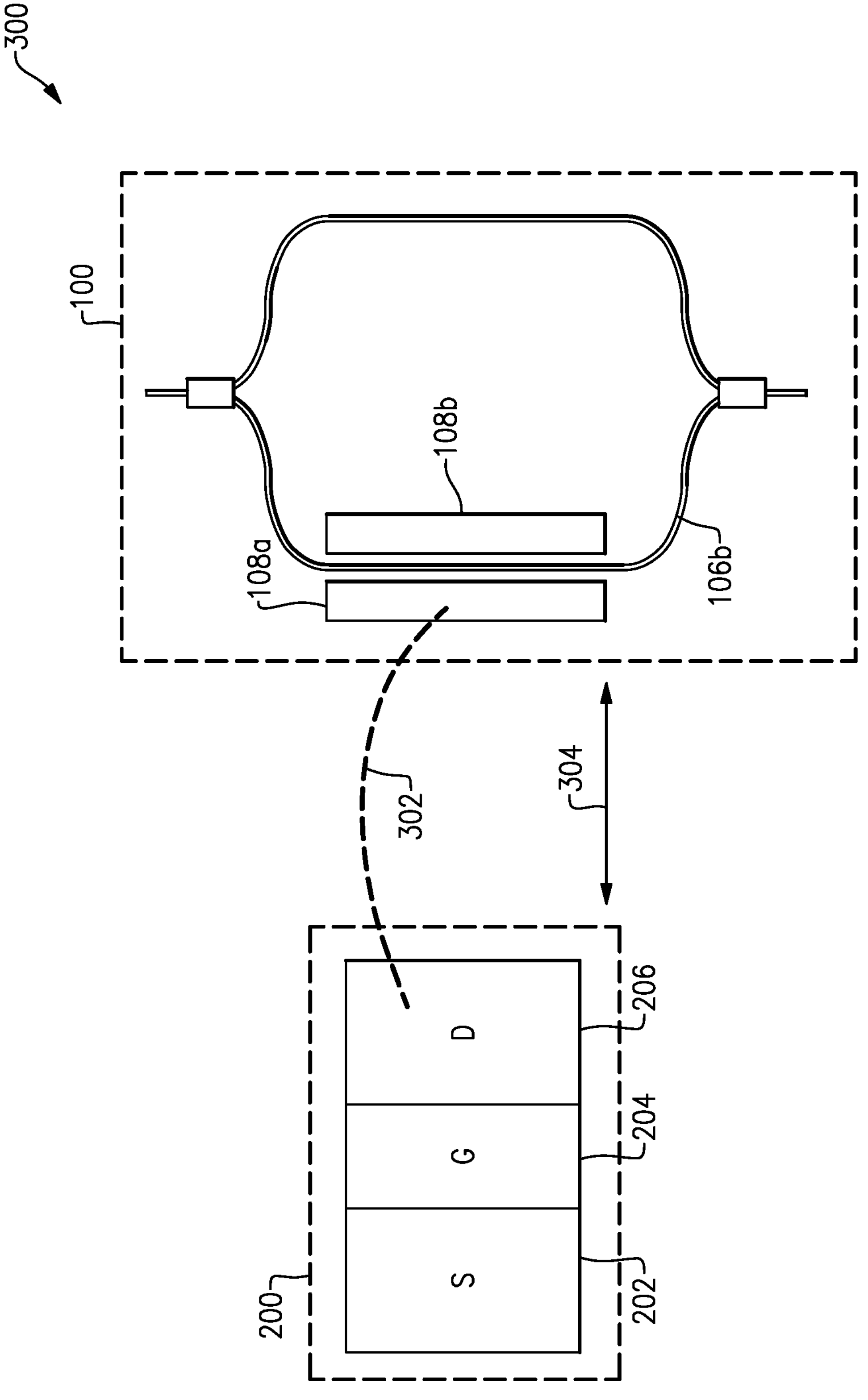


FIG.3

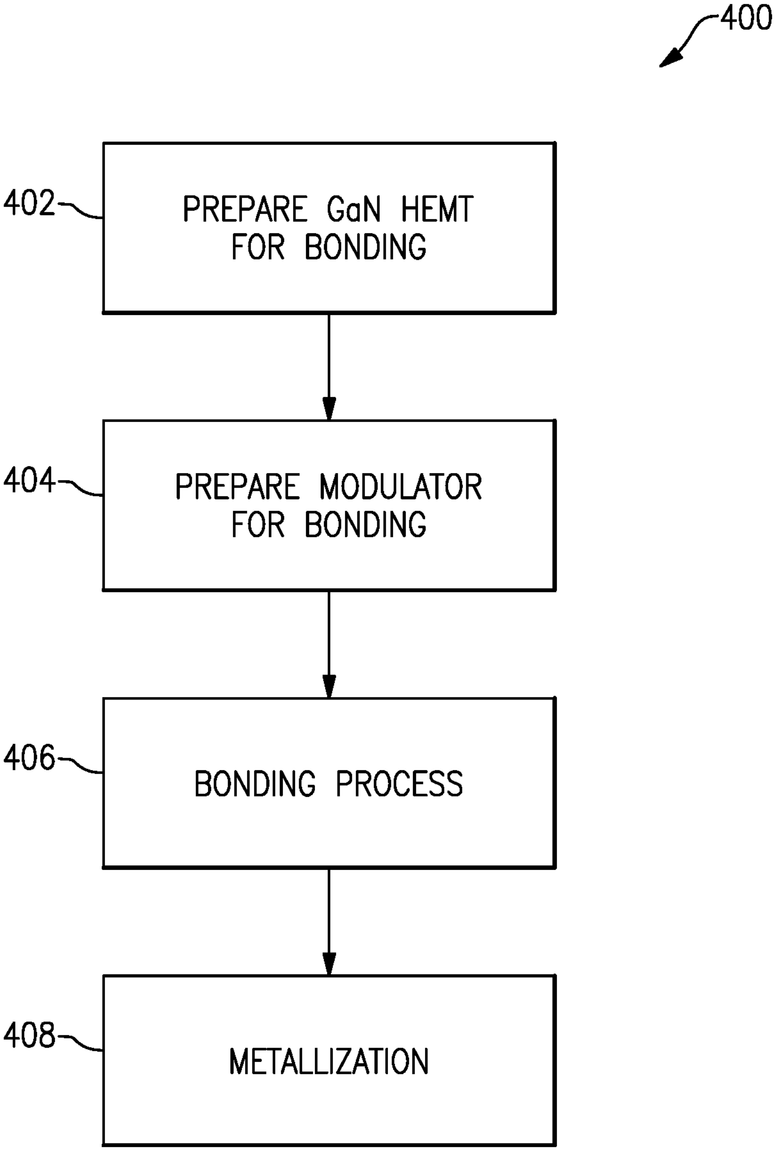

400
402
PREPARE GaN HEMT FOR BONDING
404
PREPARE MODULATOR FOR BONDING
406
BONDING PROCESS
408
METALLIZATION

FIG.4

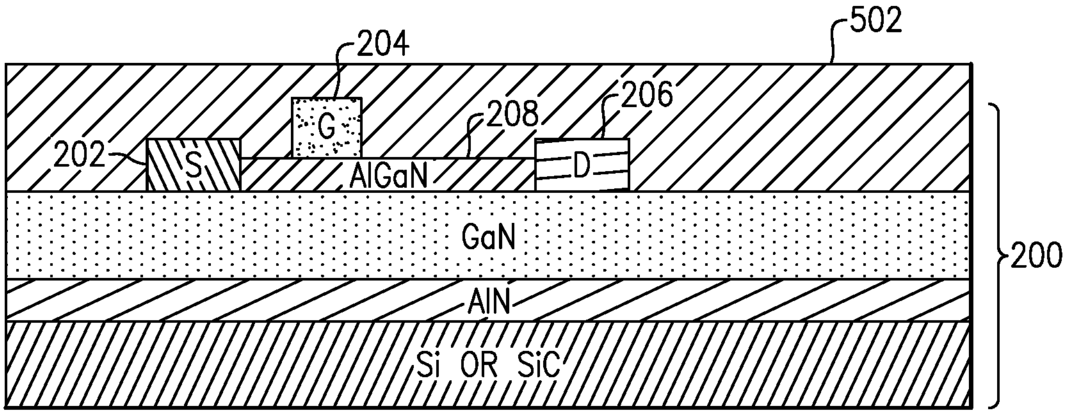


FIG.5A

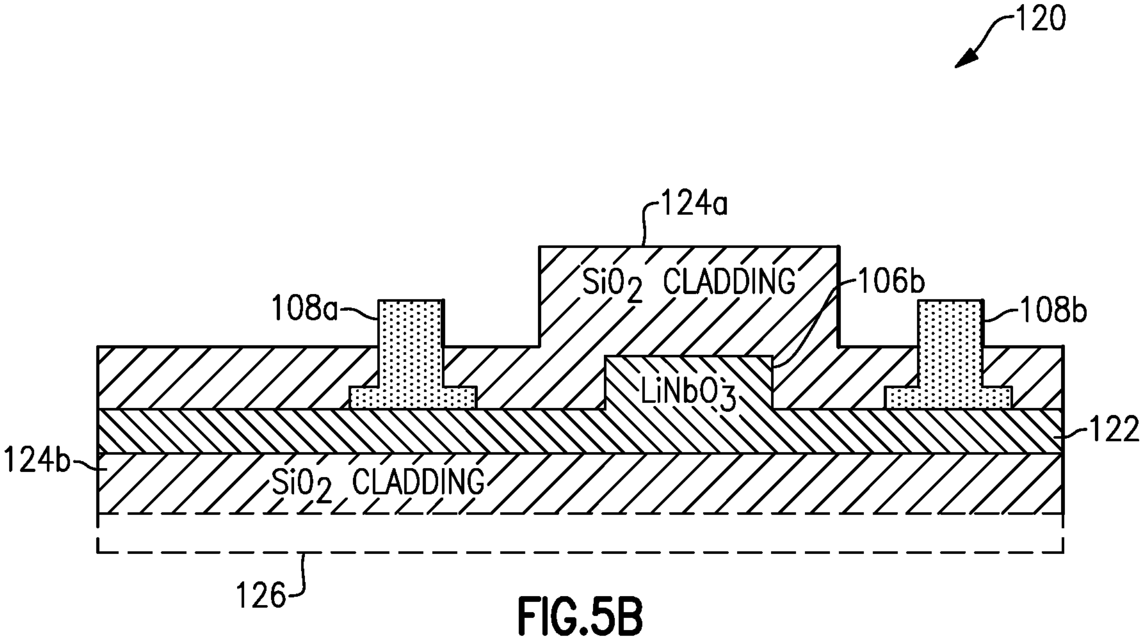

120
124a
SiO2 CLADDING
106b
108a
108b
LiNbO3
122
124b
SiO2 CLADDING
126

FIG.5B

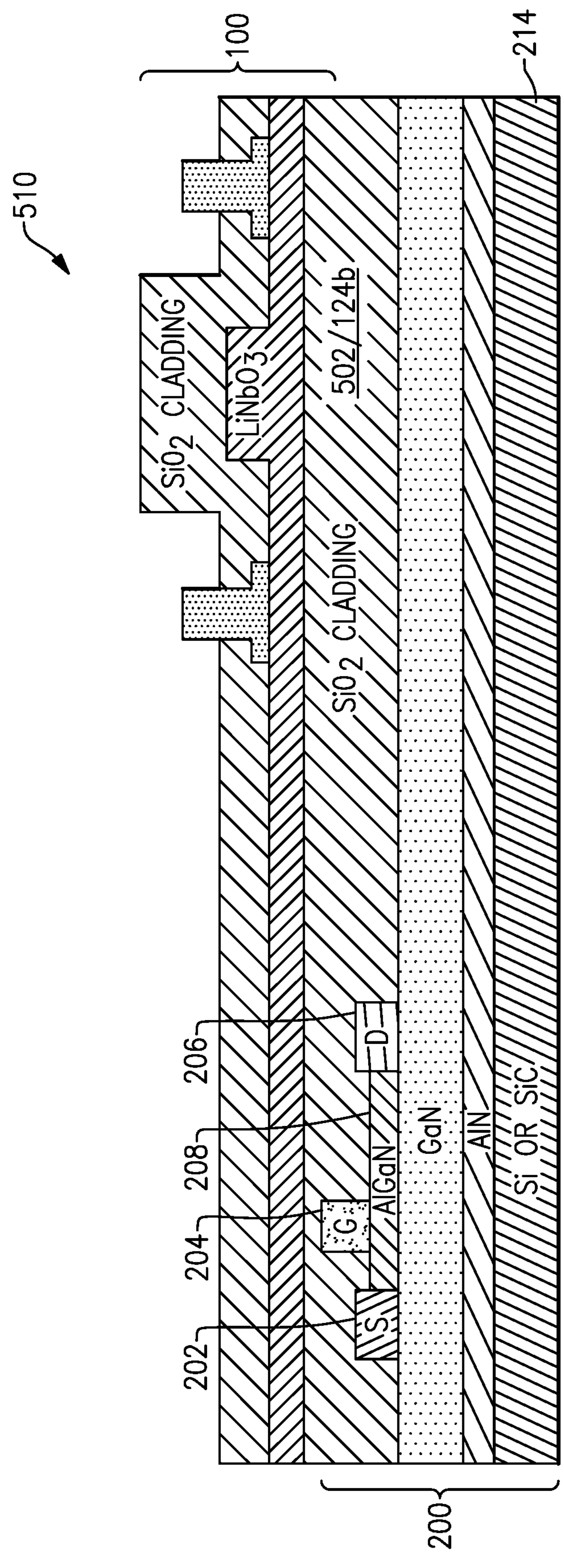

510
100
214
SiO2 CLADDING
LiNbO3
502/124b
SiO2 CLADDING
206
208
204
202
D
G
S
AlGaN
GaN
AlN
Si OR SiC
200

FIG.5C

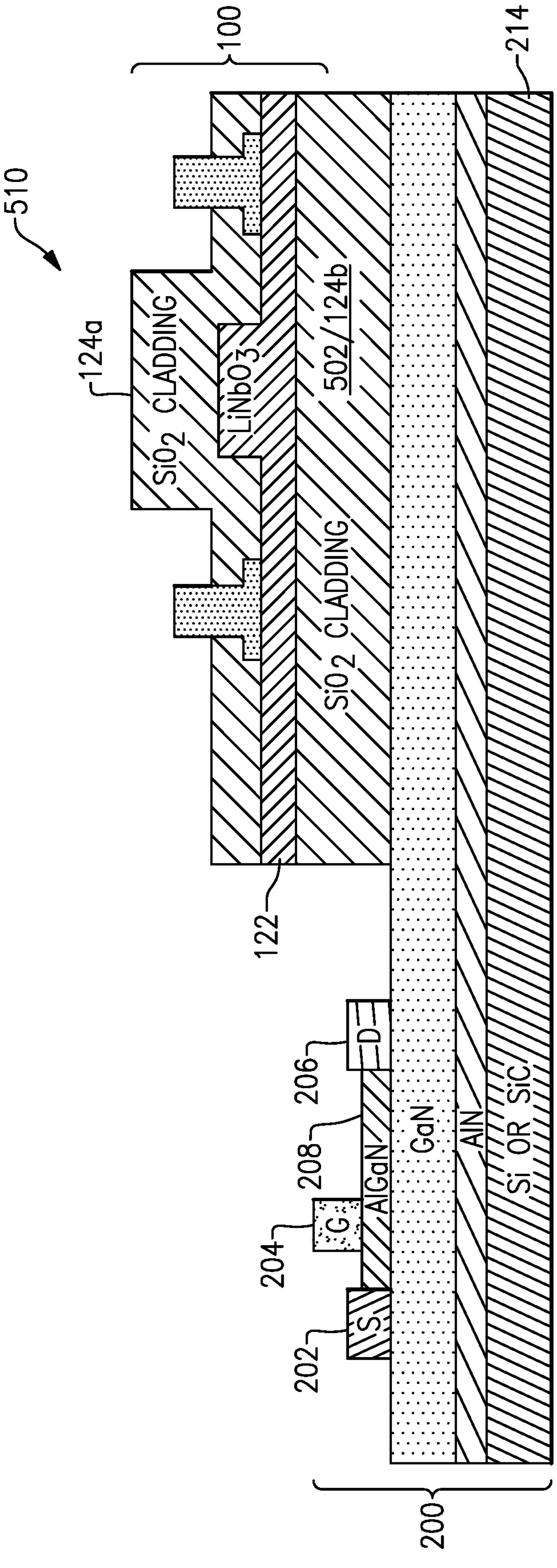

510
100
214
124a
SiO2 CLADDING
LiNbO3
502/124b
SiO2 CLADDING
122
206
D
208
AlGaN
GaN
AlN
Si OR SiC
204
G
202
S
200

FIG.5D

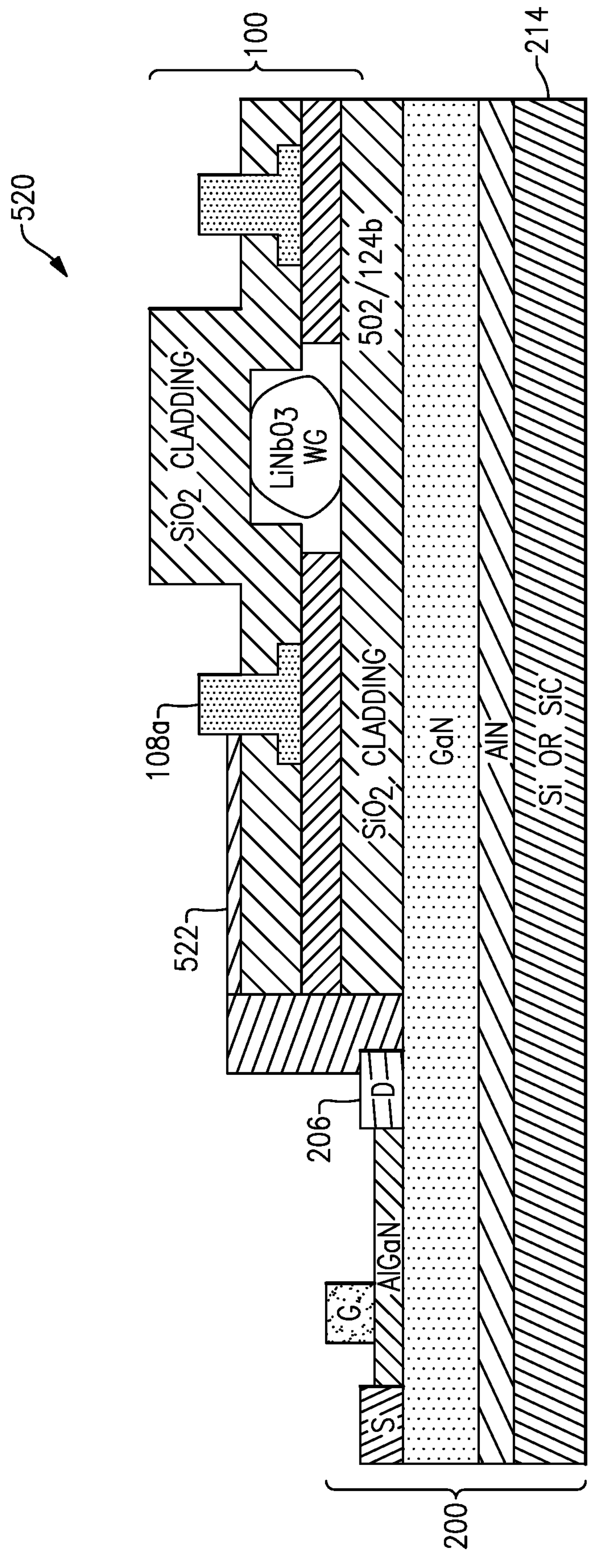

520
100
214
SiO_2 CLADDING
LiNb03 WG
502/124b
108a
SiO_2 CLADDING
GaN
AlN
Si OR SiC
522
206
D
AlGaN
G
S
200

FIG.5E

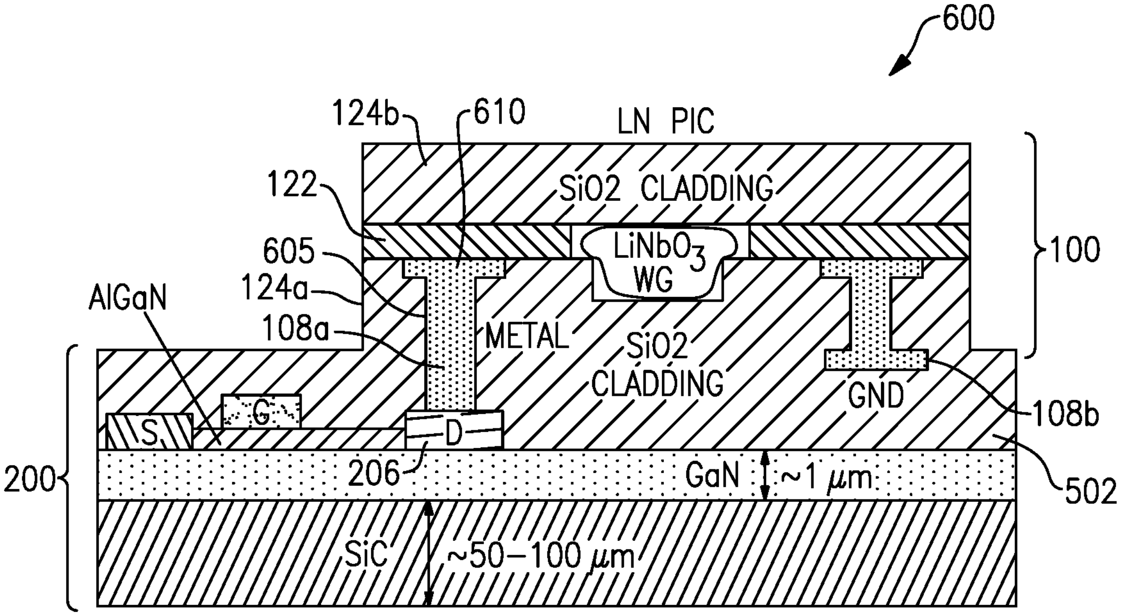

600
124b
610
LN PIC
SiO2 CLADDING
122
LiNbO$_3$
WG
605
100
124a
AlGaN
108a
METAL
SiO2
CLADDING
GND
G
S
D
108b
206
GaN
~1 μm
502
200
SiC
~50–100 μm

FIG.6A

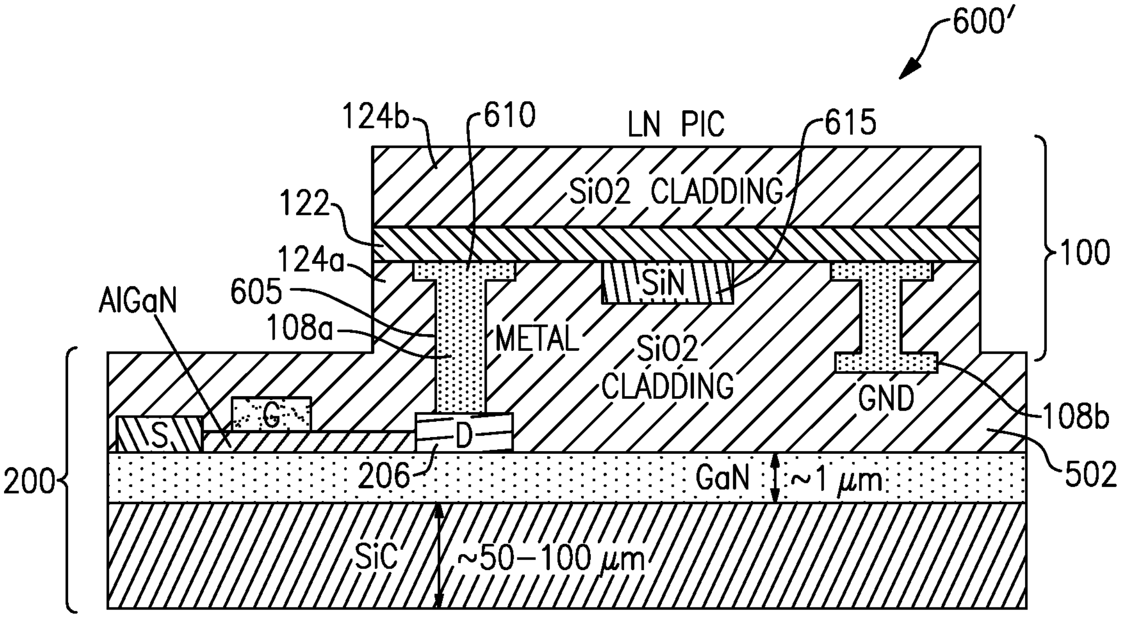

600′
124b
610
LN PIC
615
SiO2 CLADDING
122
100
124a
SiN
605
AlGaN
108a
METAL
SiO2
CLADDING
GND
108b
G
S
D
206
GaN
~1 μm
502
200
SiC
~50-100 μm

FIG.6B

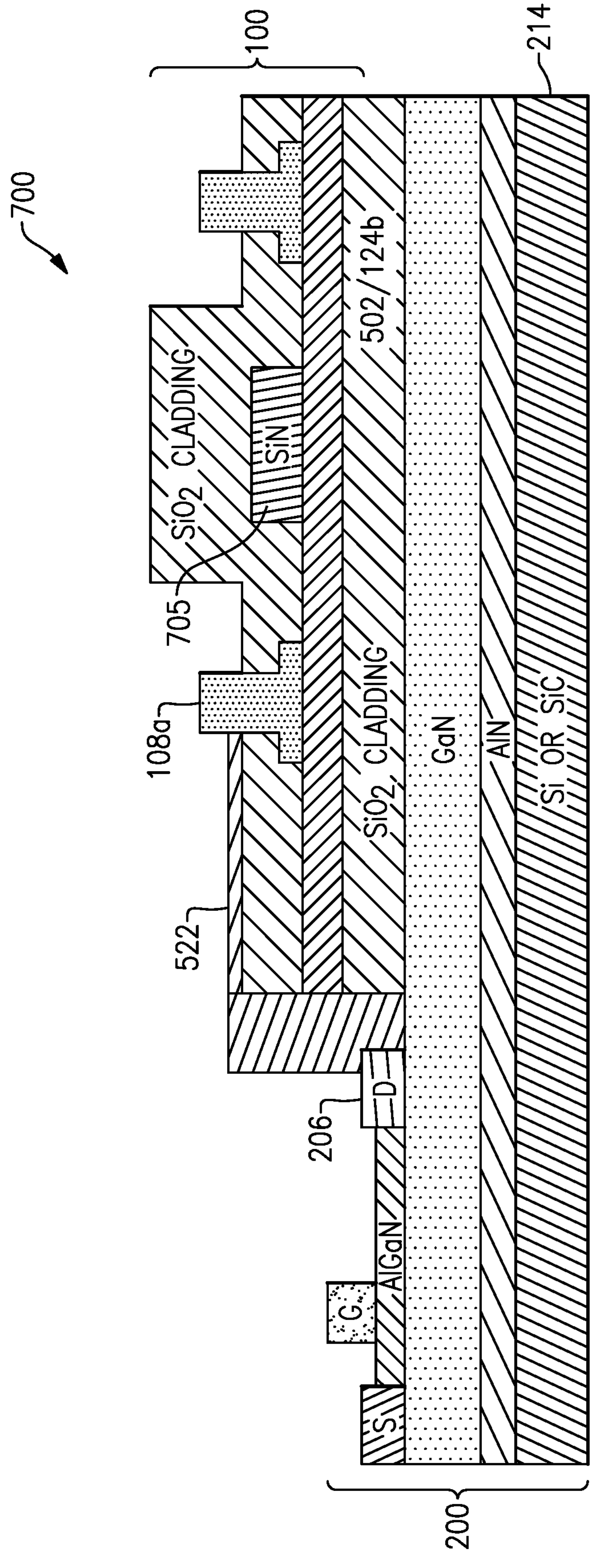

700
100
214
SiO_2 CLADDING
SiN
705
502/124b
108a
SiO_2 CLADDING
GaN
AlN
Si OR SiC
522
D
206
AlGaN
G
S
200

FIG.7

INTEGRATION OF ELECTRONICS WITH LITHIUM NIOBATE PHOTONICS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application which claims priority under 35 U.S.C. § 120 as a continuation-in-part of U.S. patent Ser. No. 18/241,715, titled "INTEGRATION OF ELECTRONICS WITH LITHIUM NIOBATE PHOTONICS," filed Sep. 1, 2023, which claims priority under 35 U.S.C. § 120 as a continuation of U.S. patent Ser. No. 17/731,369, titled "INTEGRATION OF ELECTRONICS WITH LITHIUM NIOBATE PHOTONICS," filed Apr. 28, 2022, now U.S. patent Ser. No. 11/747,704, which claims priority under 35 U.S.C. § 121 as a division of U.S. Patent application Ser. No. 16/859,454, titled "INTEGRATION OF ELECTRONICS WITH LITHIUM NIOBATE PHOTONICS," filed Apr. 27, 2020, now U.S. Pat. No. 11,340,512, each of which is hereby incorporated herein by reference for all purposes.

BACKGROUND

1. Field of Invention

[0002] Embodiments of the invention relate generally to photonic modulators and more particularly photonic modulators for converting signals carrying information in the radio frequency (RF) energy domain to signals carrying the information in the optical frequency energy domain.

2. Discussion of Related Art

[0003] As is known in the art, photonic, or electro-optic, modulators have been used to convert radio frequency (RF) energy to optical energy. Some types of photonic modulators include a waveguide structure disposed between cladding layers used to confine optical energy (e.g., from a laser) introduced into one end of the waveguide structure and then passing through the waveguide structure to a detector. One type of waveguide structure includes Lithium Niobate waveguide material which is among the most promising material for modulator devices. Due to ever-increasing performance requirements, at higher modulation frequencies (e.g., 100 GHz and above) there has been a demand to miniaturize or shorten associated electronic driving circuits and the electric wire interconnect from the electric circuit to the modulator's electrodes to enable wider frequency bandwidth and lower RF parasitic effects, where the latter can degrade performance of the modulator.

SUMMARY

[0004] One aspect of the present disclosure is directed to an electro-optical modulator assembly including a transistor including a gate, a drain, and a source disposed on a substrate, a photonic modulator including a first waveguide structure positioned between a first electrode and a second electrode, the photonic modulator being integrated with the transistor on the substrate, and a metal connection coupled between the drain of the transistor and one of the first and second electrodes of the photonic modulator.

[0005] In one embodiment, a first oxide layer disposed on a top side of the transistor is bonded to a second oxide layer disposed on a bottom side of the photonic modulator. In some embodiments, the transistor is arranged in proximity to the photonic modulator to minimize a length of the metal connection and enable operation of the photonic modulator at frequencies above 100 GHz. In certain embodiments, the transistor is a III-Nitride transistor. In one embodiment, the transistor is a Gallium Nitride (GaN) High-Electron-Mobility Transistor (HEMT).

[0006] In some embodiments, the substrate is one of a Silicon (Si) substrate and a Silicon Carbide (SiC) substrate. In certain embodiments, the photonic modulator is configured as a Mach-Zehnder interferometer (MZI) modulator and includes a second waveguide structure positioned outside the first and second electrodes. In one embodiment, the first and second waveguide structures are fabricated from at least one of Lithium Niobate ($LiNbO_3$) and Silicon Nitride (SiN) and configured to propagate an optical energy signal.

[0007] In various embodiments, the transistor is configured to receive a radio-frequency signal at the gate and to provide a modulation voltage to one of the first and second electrodes via the metal connection to induce a phase shift in the optical energy signal of the first waveguide structure. In some embodiments, the optical energy signal of the first waveguide structure is combined with the optical energy signal of the second waveguide structure to provide an optical signal having an amplitude modulation corresponding to the radio-frequency signal received at the gate of the transistor.

[0008] Another aspect of the present invention is directed to a method of manufacturing an electro-optical modulator assembly. The method includes providing a transistor including a gate, a drain, and a source disposed on a first substrate, providing a photonic modulator including a first waveguide structure positioned between a first electrode and a second electrode, the photonic modulator being disposed on a second substrate, depositing a first oxide layer over the gate, the drain, and the source of the transistor, and bonding the first oxide layer of the transistor to a second oxide layer of the photonic modulator such that the photonic modulator is integrated with the transistor on the first substrate.

[0009] In one embodiment, bonding the first oxide layer of the transistor to the second oxide layer of the photonic modulator incudes removing the second substrate to expose the second oxide layer of the photonic modulator. In some embodiments, the second substrate is removed using plasma processing and/or a back-grinding process. In certain embodiments, bonding the first oxide layer of the transistor to the second oxide layer of the photonic modulator incudes depositing the second oxide layer on a bottom side of the second substrate.

[0010] In some embodiments, the method includes removing a portion of the first oxide layer to expose the gate, the drain, and the source of the transistor, and providing a metal connection between the transistor and the photonic modulator to couple the drain of the transistor to one of the first and second electrodes of the photonic modulator. In certain embodiments, the portion of the first oxide layer is removed using a lithography process and/or an etching process. In various embodiments, the metal connection is provided between the transistor and the photonic modulator using a lithography process and/or a metal lift-off process.

[0011] In one embodiment, the transistor is a III-Nitride transistor. In some embodiments, the transistor is a Gallium Nitride (GaN) High-Electron-Mobility Transistor (HEMT). In certain embodiments, the first substrate is one of a Silicon (Si) substrate and a Silicon Carbide (SiC) substrate. In various embodiments, the photonic modulator is configured as a Mach-Zehnder interferometer (MZI) modulator and includes a second waveguide structure positioned outside the first and second electrodes. In some embodiments, the first and second waveguide structures are fabricated from at least one of Lithium Niobate ($LiNbO_3$) and Silicon Nitride (SiN) and configured to propagate optical energy.

[0012] Another aspect of the present invention is directed to an electro-optical modulator assembly. The electro-optical modulator assembly comprises a transistor including a gate, a drain, a source, and a film forming a channel layer for the transistor disposed on a substrate, a photonic modulator including a first waveguide structure positioned between a first electrode and a second electrode, the photonic modulator including a portion disposed over a portion of the transistor, and a metal connection coupled between the drain of the transistor and one of the first and second electrodes of the photonic modulator.

[0013] In some embodiments, the metal connection extends in a straight vertical path having a first end at the drain of the transistor and a second end at the one of the first and second electrodes of the photonic modulator.

[0014] In some embodiments, a first oxide layer disposed on a top side of the transistor is bonded to a second oxide layer disposed on one side of the photonic modulator.

[0015] In some embodiments, the transistor is arranged in proximity to the photonic modulator to minimize a length of the metal connection and enable operation of the photonic modulator at frequencies up to and above 100 GHz.

[0016] In some embodiments, the transistor is a III-Nitride transistor.

[0017] In some embodiments, the transistor is a III-Nitride High-Electron-Mobility Transistor (HEMT).

[0018] In some embodiments, the substrate is one of a Silicon (Si) substrate and a Silicon Carbide (SiC) substrate.

[0019] In some embodiments, the photonic modulator is configured as a Mach-Zehnder interferometer (MZI) modulator and includes a second waveguide structure positioned outside the first and second electrodes.

[0020] In some embodiments, the first and second waveguide structures are fabricated from at least one of Lithium Niobate ($LiNbO_3$) and Silicon Nitride (SiN) and configured to propagate an optical energy signal.

[0021] In some embodiments, the transistor is configured to receive a radio-frequency signal at the gate and to provide a modulation voltage to one of the first and second electrodes via the metal connection to induce a phase shift in the optical energy signal of the first waveguide structure.

[0022] In some embodiments, the optical energy signal of the first waveguide structure is combined with the optical energy signal of the second waveguide structure to provide an optical signal having an amplitude modulation corresponding to the radio-frequency signal received at the gate of the transistor.

[0023] In some embodiments, at least one of the first and second waveguide structures are fabricated from a SiN film disposed on a slab of $LiNbO_3$.

[0024] In some embodiments, the photonic modulator is disposed on the film forming the channel layer for the transistor.

[0025] In some embodiments, the first waveguide structure is formed on a lower side of a slab of $LiNbO_3$, the lower side of the slab of $LiNbO_3$ facing the transistor.

[0026] Another aspect of the present invention is directed to a method of manufacturing an electro-optical modulator assembly. The method comprises forming a transistor including a gate, a drain, and a source disposed on a first substrate, forming a photonic modulator including a first waveguide structure positioned between a first electrode and a second electrode, the photonic modulator being disposed on a second substrate, depositing an oxide layer over the gate, the drain, and the source of the transistor, and bonding the oxide layer of the transistor to the photonic modulator such that the photonic modulator is integrated with the transistor and the photonic modulator is at least partially disposed over the transistor.

[0027] In some embodiments, bonding the oxide layer of the transistor to the photonic modulator includes bonding the photonic modulator to the transistor in a position in which the photonic modulator is disposed over a film forming a channel layer for the transistor.

[0028] In some embodiments, the method further comprises forming a metal connection between the transistor and the photonic modulator to couple the drain of the transistor to one of the first and second electrodes of the photonic modulator.

[0029] In some embodiments, forming the metal connection includes forming the metal connection includes forming the metal connection in a straight vertical path having a first end at the drain of the transistor and a second end at the one of the first and second electrodes of the photonic modulator.

[0030] In some embodiments, the transistor is a III-Nitride transistor.

[0031] In some embodiments, the transistor is a Gallium Nitride (GaN) High-Electron-Mobility Transistor (HEMT).

[0032] In some embodiments, the first substrate is one of a Silicon (Si) substrate and a Silicon Carbide (SiC) substrate.

[0033] In some embodiments, the photonic modulator is configured as a Mach-Zehnder interferometer (MZI) modulator and includes a second waveguide structure positioned outside the first and second electrodes.

[0034] In some embodiments, the first and second waveguide structures are fabricated from at least one of Lithium Niobate ($LiNbO_3$) slab and Silicon Nitride (SiN) ridge layer and configured to propagate optical energy.

[0035] In some embodiments, forming the photonic modulator includes forming the photonic modulator with a waveguide formed of one of silicon, gallium nitride, indium phosphide, gallium arsenide, a III-Nitride material, or a III-V material.

[0036] In some embodiments, the first waveguide structure is formed on a lower side of a slab of $LiNbO_3$, the lower side of the slab of $LiNbO_3$ facing the transistor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0037] Various aspects of at least one embodiment are discussed below with reference to the accompanying figures, which are not intended to be drawn to scale. The figures are included to provide illustration and a further understanding of the various aspects and embodiments, and are incorporated in and constitute a part of this specification, but are not intended as a definition of the limits of the invention. In the figures, each identical or nearly identical component that is illustrated in various figures is represented by a like numeral. For purposes of clarity, not every component may be labeled in every figure. In the figures:

[0038] FIG. **1**A is a diagram illustrating a top-down view of a photonic modulator;

[0039] FIG. **1**B is a diagram illustrating a cross-sectional view of a photonic modulator;

[0040] FIG. **1**C is a diagram illustrating a cross-sectional view of a photonic modulator;

[0041] FIG. **2** is a diagram illustrating a cross-sectional view of a III-Nitride electronic device;

[0042] FIG. **3** is a diagram illustrating an electro-optical modulator arrangement according to one embodiment;

[0043] FIG. **4** is a flow chart illustrating a method for manufacturing an electro-optical modulator assembly according to one embodiment;

[0044] FIG. **5**A is a diagram illustrating a cross-sectional view of a III-Nitride electronic device according to one embodiment;

[0045] FIG. **5**B is a diagram illustrating a cross-sectional view of a photonic modulator according to one embodiment;

[0046] FIG. **5**C is a diagram illustrating a cross-sectional view of a III-Nitride electronic device integrated with a photonic modulator according to one embodiment;

[0047] FIG. **5**D is a diagram illustrating a cross-sectional view of a III-Nitride electronic device integrated with a photonic modulator according to one embodiment;

[0048] FIG. **5**E is a diagram illustrating a cross-sectional view of an electro-optical modulator assembly according to one embodiment;

[0049] FIG. **6**A is a diagram illustrating a cross-sectional view of a III-Nitride electronic device integrated with a photonic modulator according to one embodiment;

[0050] FIG. **6**B is a diagram illustrating a cross-sectional view of a III-Nitride electronic device integrated with a photonic modulator according to one embodiment; and

[0051] FIG. **7** is a diagram illustrating a cross-sectional view of a III-Nitride electronic device integrated with a photonic modulator according to one embodiment.

DETAILED DESCRIPTION

[0052] It is to be appreciated that embodiments of the methods and apparatuses discussed herein are not limited in application to the details of construction and the arrangement of components set forth in the following description or illustrated in the accompanying drawings. The methods and apparatuses are capable of implementation in other embodiments and of being practiced or of being carried out in various ways. Examples of specific implementations are provided herein for illustrative purposes only and are not intended to be limiting. Also, the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use herein of "including," "comprising," "having," "containing," "involving," and variations thereof is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. References to "or" may be construed as inclusive so that any terms described using "or" may indicate any of a single, more than one, and all of the described terms. Any references to front and back, left and right, top and bottom, upper and lower, and vertical and horizontal are intended for convenience of description, not to limit the present systems and methods or their components to any one positional or spatial orientation.

[0053] As discussed above, photonic modulators can be used to convert RF energy signals into optical energy signals. In some cases, photonic modulators may utilize waveguide structures including different photonic materials integrated with Lithium Niobate ($LiNbO_3$) to provide improved performance. For example, FIG. **1**A illustrates a diagram of a Mach-Zehnder interferometer (MZI) modulator **100**. The modulator **100** includes an input **102**, an output **104**, a waveguide structure **106***a*, **106***b* (referred to collectively herein as waveguide structure **106**), a first electrode **108***a*, and a second electrode **108***b*. In one example, the waveguide structure **106** may include a first arm **106***a* and a second arm **106***b*. An optical energy signal (e.g., from a laser) may be provided to the input **102** and split between the two arms **106***a*, **106***b*. The arms **106***a*, **106***b* may allow the optical energy signal to propagate from the input **102** to the output **104**. A modulation voltage may be applied to the first electrode **108***a* and/or the second electrode **108***b* to induce a phase shift in the optical energy signal of the second arm **106***b* (i.e., the modulating arm). In some examples, a modulation voltage may also be applied to third and fourth electrodes (not shown) to induce a phase shift in the optical energy signal of the first arm **106***a*. In some examples, the modulation voltage applied to the electrode(s) may correspond to information carried by an RF energy signal. The optical energy signals of the first and second arms **106***a*, **106***b* may constructively and/or de-constructively combine to produce output optical energy having an amplitude modulation corresponding to the information carried by the RF energy signal.

[0054] FIG. **1**B illustrates a cross sectional view of a modulation section **120** of an MZI modulator. In one example, the modulation section **120** may correspond to the electrodes **108***a*, **108***b*, and the waveguide structure of the second arm **106***b* of the modulator **100** of FIG. **1**A. As shown, the waveguide structure of the second arm **106***b* may be defined by directly patterning a slab of Lithium Niobate ($LiNbO_3$) material **122**. The waveguide structure of the second arm **106***b* is surrounded by Silicon Dioxide (SiO_2) cladding layers **124***a*, **124***b*. The electrodes **108***a*, **108***b* may be fixed to the slab of $LiNbO_3$ material **122** and partially covered by the SiO_2 cladding layer **124***a*. In some examples, the waveguide structure of the second arm **106***b*, the slab of $LiNbO_3$ material **122**, the electrodes **108***a*, **108***b*, and the cladding layers **124***a*, **124***b* may be disposed on a Silicon (Si) substrate **126**. While not shown, the waveguide structure of the first arm **106***a* of the modulator **100** may be configured similar to the waveguide structure of the second arm **106***b*. For example, the waveguide structure of the first arm **106***a* may be defined by directly patterning a slab of $LiNbO_3$ material **122**, surrounding the patterned slab of $LiNbO_3$ material **122** by SiO_2 cladding layers **124***a*, **124***b*, and disposing the structure on a Si substrate **126**, optionally the same Si substrate **126** used in the waveguide structure of the second arm **106***b*.

[0055] In some examples, the waveguide structures **106***a*, **106***b* may be configured differently. For example, FIG. **1**C illustrates a cross sectional view of a modulation section **140** of an MZI modulator (e.g., modulator **100**). In one example, the modulation section **140** may be substantially the same as the modulation section **120** of FIG. **1**B, except the waveguide structure of the second arm **106***b* is configured differently. As shown, the waveguide structure of the second arm **106***b* is defined by patterning a Silicon Nitride (SiN) film on the slab of $LiNbO_3$ material **122**. Likewise, the waveguide structure of the first arm **106***a* may be configured similarly.

[0056] As discussed above, when operating photonic modulators such as the modulator **100** at high frequencies (e.g., above 100 GHz), RF parasitic effects (e.g., signal reflection, propagation loss, electromagnetic interference, etc.) can degrade performance. In some implementations, such modulators can be designed with a miniaturized form (e.g., relative to wavelength) to suppress RF parasitic effects within the modulator. However, reducing the size of the modulator can increase the modulation voltage required to achieve the desired phase shift (e.g., 180°). In addition, the distance between voltage circuitry configured to apply the modulation voltage to the electrode(s) and the modulator may contribute to additional RF loss and/or reflections.

[0057] A compact, high-frequency photonic modulator arrangement is provided herein. In at least one embodiment, a photonic modulator is integrated with a III-Nitride electronic device. More specifically, the photonic modulator is bonded to the electronic device substrate to reduce RF parasitic effects between the devices and enable high frequency operation of the modulator (e.g., above 100 GHz).

[0058] As discussed above, photonic modulators used in high frequency applications may operate with an increased modulation voltage. As such, voltage circuitry configured to provide the modulation voltage to the electrode(s) of the modulator may include semiconductor devices capable of providing large voltages without entering a breakdown region at high frequencies. In one example, the voltage circuitry may include one or more III-Nitride electronic devices. For example, the voltage circuitry may include one or more Gallium Nitride (GaN) High-Electron-Mobility Transistors (HEMT) to provide the increased modulation voltage. As known to those skilled in the art, GaN HEMTs can provide high breakdown voltages while operating at high frequencies (e.g., above 100 GHz). In some examples, GaN HEMTs can be utilized to provide low noise amplification. FIG. **2** illustrates a cross sectional view of an example of a GaN HEMT **200**. As shown, the GaN HEMT **200** includes a source **202**, a gate **204**, and a drain **206**. In one example, an Aluminum Gallium Nitride (AlGaN) barrier layer **208** is included between the source **202**, the gate **204**, and the drain **206**. In other examples, the barrier layer **208** can be made from InAlN, InAlGaN, or ScAlN materials. The source **202** and the drain **206** are fixed to a GaN channel layer **210** and an Aluminum Nitride (AlN) nucleation (or buffer) layer **212** is disposed between the GaN channel layer **210** and a substrate **214**. In some examples, the substrate **214** may be made from Si; however, in other examples the substrate may be made from a Silicon Carbide (SiC) material.

[0059] FIG. **3** illustrates an electro-optical modulator arrangement **300** in accordance with aspects described herein. In one example, the GaN HEMT **200** of FIG. **2** is coupled to the modulator **100** of FIG. **1**A. As shown, the drain **206** of the GaN HEMT **200** is coupled to the electrode **108***a* of the modulator **100** via a metal connection **302**. The GaN HEMT **200** is configured to provide a modulation voltage via the drain **206** to the electrode **108***a* to modulate the optical energy of the second arm **106***b*. In some examples, the electrode **108***b* may be coupled to ground or another voltage source. While not shown, the GaN HEMT **200** may be configured to operate with other circuitry to provide the modulation voltage to the electrode **108***a*. For example, an RF modulation source may be coupled to the gate **204** and the source **202** may be coupled to ground or another voltage source. As such, the RF modulation source may provide an RF signal to the gate **204** to turn the GaN HEMT **200** on and off, providing the modulation voltage at the drain **206** corresponding to the RF signal. In some examples, the GaN HEMT **200** may be configured to amplify the modulation voltage provided at the drain **206**.

[0060] In one example, the distance **304** represents a physical distance between the drain **206** and the electrode **108***a*. As such, the electrical length of the metal connection **302** may correspond to the distance **304**. As discussed above, the distance between the voltage circuitry (i.e., the GaN HEMT **200**) and the modulator **100** may contribute to parasitic RF loss. As such, reducing the distance **304** between the drain **206** and the electrode **108***a* may improve performance of the modulator **100**.

[0061] FIG. **4** illustrates a method **400** of manufacturing an electro-optical modulator assembly in accordance with aspects described herein. In one example, the electro-optical modulator assembly corresponds to a photonic modulator integrated with an electronic device. For example, the electro-optical modulator assembly may correspond to the electro-optical modulator arrangement **300** of FIG. **3**. In some examples, the method **400** may allow for the distance **304** between the GaN HEMT **200** and the modulator **100** to be reduced, improving performance of the modulator **100** at high frequencies.

[0062] In one example, the method **400** includes bonding the modulator **100** to the GaN HEMT **200** using an oxide-oxide bonding process. As such, at block **402**, the GaN HEMT **200** is prepared for the oxide-oxide bonding process. As shown in FIG. **5**A, an SiO_2 layer **502** is deposited over the GaN HEMT **200**. In some examples, the thickness of the SiO_2 layer **502** may correspond to the thickness of certain features of the GaN HEMT **200**. For example, the SiO_2 layer **502** may be thick enough to cover metal contacts corresponding to the source **202**, the gate **204**, and the drain **206** of the GaN HEMT **200**. In certain examples, a planarization process may be utilized to flatten the top of the SiO_2 layer **502**.

[0063] Similarly, at block **404**, the modulator **100** is prepared for the oxide-oxide bonding process. In one example, the Si substrate **126** of the modulator **100** may be removed to expose the SiO_2 cladding layer **124***b*. FIG. **5**B illustrates the modulation section **120** of the modulator **100** with the Si substrate **126** removed. In some examples, the Si substrate **126** may be removed using plasma processing and/or a back-grinding process. Alternatively, in other examples, a thin SiO_2 layer may be deposited on the back (i.e., bottom) of the Si substrate **126**. In some examples, it may be preferred to remove the Si substrate **126** to maintain or improve performance of the modulator **100** at high frequencies (e.g., above 100 GHz). While not shown, in other examples, the modulator **100** may be configured with the modulation section **140** of FIG. **1**C and may be modified in a similar manner.

[0064] At block **406**, the modulator **100** is integrated onto the substrate **214** of the GaN HEMT **200**. As shown in FIG. **5**C, the SiO_2 cladding layer **124***b* of the modulator **100** is bonded to the SiO_2 layer **502** of the GaN HEMT **200** using an oxide-oxide bonding process to produce an integrated device **510**. In one example, the area (e.g., layers) above the GaN HEMT **200** may be removed to provide access to the source **202**, the gate **204**, and the drain **206**. For example, as shown in FIG. **5**D, portions of the layers **122**, **124***a*, **124***b*, and **502** above the source **202**, the gate **204**, and the drain **206** may be removed from the integrated device **510** using a lithography and/or etching process. In other examples, the portion of the SiO_2 layer **502** covering the source **202**, gate **204**, and drain **208** of the GaN HEMT **200** may be removed prior to the oxide-oxide bonding process (e.g., prior to block **406**) such that the source **202**, gate **204**, and drain **208** of the GaN HEMT **200** remain exposed post-bond.

[0065] At block **408**, a metallization process is applied to the integrated device **510**. As shown in FIG. **5**E, the metallization process may be utilized to produce a metal connection **522** between the GaN HEMT **200** and the modulator **100** to provide an electro-optical modulator assembly **520**. In one example, the metal connection **522** may correspond to the metal connection **302** of FIG. **3**. The metal connection **522** may couple the drain **206** of the GaN HEMT **200** to the electrode **108***a* of the modulator **100**. In some examples, the metallization process may include a lithography and/or a metal lift-off process to connect the drain **206** to the electrode **108***a*. While not shown, in other examples, a similar process may be utilized to couple the electrode **108***b* to ground or a different voltage source.

[0066] In some examples, by bonding the modulator **100** to the substrate **214** of GaN HEMT **200**, the modulator **100** can be arranged in close proximity (e.g., microns) to the GaN HEMT **200**. Being that the modulator **100** and the GaN HEMT **200** are in close proximity, the length of the metal connection **522** may be relatively short and the distance between the drain **206** of the GaN HEMT **200** and the electrode **108***a* (e.g., the distance **304**) may be reduced significantly. As such, RF parasitic effects associated with the electrical connection between the modulator **100** and the GaN HEMT **200** can be reduced, and the modulator **100** may be enabled to operate at even higher frequencies (e.g., THz range).

[0067] An alternative embodiment of an electro-optical modulator assembly is illustrated in FIG. **6**A indicated generally at **600**. The electro-optical modulator assembly **600** includes a GaN HEMT **200** and a modulator section **100** as in the electro-optic modulator assembly **520** illustrated in FIG. **5**E. The electro-optical modulator assembly **600**, however, is formed by bonding the upper SiO_2 cladding layer **124***a* of the modulator section (illustrated in FIG. **5**B) to the SiO_2 layer **502** formed on the GaN HEMT **200** (illustrated in FIG. **5**A) rather than by bonding the lower SiO_2 cladding layer **124***b* of the modulator section to the SiO_2 layer **502** formed on the GaN HEMT **200** as in the electro-optic modulator assembly **520** illustrated in FIG. **5**E. Additional SiO_2 may be deposited and planarized on the SiO_2 cladding layer **124***a* of the modulator section prior to bonding it to the SiO_2 layer **502** formed on the GaN HEMT **200** to provide for planar bonding surfaces.

[0068] The slab of Lithium Niobate ($LiNbO_3$) material **122** of the modulator section **100** thus includes a portion located directly over a portion of the GaN HEMT **200**. Specifically, the first electrode **108***a* of the modulator section **100** may be disposed directly over the drain **206** of the GaN HEMT **200**. A via hole **605** may be etched through the SiO_2 layer **502** so that a conductive via may be formed to effectively extend the first electrode **108***a* so that it makes electrical contact with the drain **206** of the GaN HEMT **200**. The via hole **605** may be etched and filled with metal prior to bonding the modulator section **100** to the GaN HEMPT **200**. The conductive via/first electrode **108***a* may extend straight down from an electrical contact **610** on the slab of $LiNbO_3$ **122** to the drain **206** of the GaN HEMPT. The waveguide is disposed on a lower side of the slab of $LiNbO_3$ **122** which is the side of the slab of $LiNbO_3$ **122** facing the GaN HEMPT **200**.

[0069] FIG. **6**A illustrates the waveguide as being formed of $LiNbO_3$ (labelled "$LiNbO_3$ WG") but in other embodiments the waveguide may be formed of SiN such as in the example of the modulator shown in FIG. **1**C. FIG. **6**B illustrates a modification to the electro-optical modulator assembly **600**, indicated generally at **600'**, in which the $LiNbO_3$ ridge waveguide has been replaced with a SiN ridge waveguide **615**. FIG. **7** illustrates a modification to the electro-optic modulator assembly **520** illustrated in FIG. **5**E to form an electro-optic modulator assembly **700** including a SiN waveguide **705** disposed on the $LiNbO_3$ slab **122**. It is to be understood that the material of the waveguide of any embodiments of electro-optic modulator assemblies as disclosed herein is not limited to $LiNbO_3$ or SiN, but may be any suitable waveguide material, for example, any of silicon, gallium nitride, indium phosphide, gallium arsenide, or any other suitable III-Nitride or III-V materials.

[0070] In the electro-optical modulator assembly **600** RF parasitic effects associated with the electrical connection between the modulator **100** and the GaN HEMT **200** may be reduced as compared to the electro-optic modulator assembly **520** due to an even shorter distance between the drain **206** of the GaN HEMT **200** and the electrode **108***a*. In addition, the complexity of fabrication of the modulator on the GaN HEMT transistor with all the metal processing may be reduced. The second electrode **108***b* of the modulator section **100** may be electrically connected to ground as illustrated.

[0071] A method of forming the electro-optical modulator assembly **600** may be substantially the same as the method of forming the electro-optic modulator assembly **520** except that the modulator section **100** and GaN HEMT **200** are bonded by bonding the upper SiO_2 cladding layer **124***a* of the modulator section to the SiO_2 layer **502** formed on the GaN HEMT **200** (illustrated in FIG. **5**A) rather than by bonding the lower SiO_2 cladding layer **124***b* of the modulator section to the SiO_2 layer **502** formed on the GaN HEMT **200**. Further the electrical connection between the drain **206** of the GaN HEMT and the electrical contact **610** on the slab of $LiNbO_3$ **122** is formed by contacting the metal vias already implemented through the SiO_2 layer **502** and **605**, that electrically contacts and forms an extension of the electrode **108***a* of the modulator **100**.

[0072] It should be appreciated that embodiments described herein are not limited to a particular type of III-Nitride electronic device. As described above, a GaN HEMT can be integrated with a photonic modulator to provide improved high frequency performance; however, in other examples, different III-Nitride materials and/or devices may be utilized. For example, depending on the implementation, the method **400** may be adapted to integrate an Indium Nitride (InN) HEMT with the photonic modulator (e.g., depositing SiO_2 on top of the InN HEMT for bonding). In alternative embodiments, devices other than III-Nitride devices, such as GaAs, InP, SiC, and Si based devices, may be integrated with photonic modulators depending on the performance requirements for specific applications. In addition, in some examples, the method **400** may be carried out using individual devices (i.e., chips); however, in other examples, the method **400** may be carried out at the wafer-level.

[0073] Likewise, it should be appreciated that embodiments described herein are not limited to a specific type of photonic modulator. While the use of an MZI modulator is described above, in other examples, III-Nitride electronic devices can be integrated with different types of modulators (e.g., a resonator modulator).

[0074] Accordingly, various aspects and examples described herein provide a compact, high-frequency photonic modulator arrangement. In at least one embodiment, a photonic modulator is integrated with an III-Nitride electronic device. More specifically, the photonic modulator is bonded to the electronic device substrate to reduce RF parasitic effects between the devices and enable high frequency operation of the modulator (e.g., above 100 GHz).

[0075] Having described above several aspects of at least one example, it is to be appreciated various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended to be part of this disclosure and are intended to be within the scope of the invention. Accordingly, the foregoing description and drawings are by way of example only, and the scope of the invention should be determined from proper construction of the appended claims, and their equivalents.

What is claimed is:

1. An electro-optical modulator assembly comprising:

a transistor including a gate, a drain, a source, and a film forming a channel layer for the transistor disposed on a substrate;

a photonic modulator including a first waveguide structure positioned between a first electrode and a second electrode, the photonic modulator including a portion disposed over a portion of the transistor; and

a metal connection coupled between the drain of the transistor and one of the first and second electrodes of the photonic modulator.

2. The electro-optical modulator assembly of claim **1**, wherein the metal connection extends in a vertical path having a first end at the drain of the transistor and a second end at the one of the first and second electrodes of the photonic modulator.

3. The electro-optical modulator assembly of claim **1**, wherein a first oxide layer disposed on a top side of the transistor is bonded to a second oxide layer disposed on one side of the photonic modulator.

4. The electro-optical modulator assembly of claim **1**, wherein the transistor is arranged in proximity to the photonic modulator to minimize a length of the metal connection and enable operation of the photonic modulator at frequencies up to and above 100 GHz.

5. The electro-optical modulator assembly of claim **1**, wherein the transistor is a III-Nitride transistor.

6. The electro-optical modulator assembly of claim **5**, wherein the transistor is a III-Nitride High-Electron-Mobility Transistor (HEMT).

7. The electro-optical modulator assembly of claim **1**, wherein the substrate is one of a Silicon (Si) substrate and a Silicon Carbide (SiC) substrate.

8. The electro-optical modulator assembly of claim **1**, wherein the photonic modulator is configured as a Mach-Zehnder interferometer (MZI) modulator and includes a second waveguide structure positioned outside the first and second electrodes.

9. The electro-optical modulator assembly of claim **8**, wherein the first and second waveguide structures are fabricated from at least one of Lithium Niobate ($LiNbO_3$) and Silicon Nitride (SiN) and configured to propagate an optical energy signal.

10. The electro-optical modulator assembly of claim **9**, wherein the transistor is configured to receive a radio-frequency signal at the gate and to provide a modulation voltage to one of the first and second electrodes via the metal connection to induce a phase shift in the optical energy signal of the first waveguide structure.

11. The electro-optical modulator assembly of claim **10**, wherein the optical energy signal of the first waveguide structure is combined with the optical energy signal of the second waveguide structure to provide an optical signal having an amplitude modulation corresponding to the radio-frequency signal received at the gate of the transistor.

12. The electro-optical modulator assembly of claim **8**, wherein at least one of the first and second waveguide structures are fabricated from a SiN film disposed on a slab of $LiNbO_3$.

13. The electro-optical modulator assembly of claim **1**, wherein the photonic modulator is disposed on the film forming the channel layer for the transistor.

14. The electro-optical modulator assembly of claim **1**, wherein the first waveguide structure is formed on a lower side of a slab of $LiNbO_3$, the lower side of the slab of $LiNbO_3$ facing the transistor.

15. A method of manufacturing an electro-optical modulator assembly, the method comprising:

forming a transistor including a gate, a drain, and a source disposed on a first substrate;

forming a photonic modulator including a first waveguide structure positioned between a first electrode and a second electrode, the photonic modulator being disposed on a second substrate;

depositing an oxide layer over the gate, the drain, and the source of the transistor; and

bonding the oxide layer of the transistor to the photonic modulator such that the photonic modulator is integrated with the transistor and the photonic modulator is at least partially disposed over the transistor.

16. The method of claim **15**, wherein bonding the oxide layer of the transistor to the photonic modulator includes bonding the photonic modulator to the transistor in a position in which the photonic modulator is disposed over a film forming a channel layer for the transistor.

17. The method of claim **15**, further comprising forming a metal connection between the transistor and the photonic modulator to couple the drain of the transistor to one of the first and second electrodes of the photonic modulator, forming the metal connection including forming the metal connection in a vertical path having a first end at the drain of the transistor and a second end at the one of the first and second electrodes of the photonic modulator.

18. The method of claim **15**, wherein the photonic modulator is configured as a Mach-Zehnder interferometer (MZI) modulator and includes a second waveguide structure positioned outside the first and second electrodes, and wherein the first and second waveguide structures are fabricated from at least one of Lithium Niobate ($LiNbO_3$) and Silicon Nitride (SiN) and configured to propagate optical energy.

19. The method of claim **15**, wherein forming the photonic modulator includes forming the photonic modulator with a waveguide formed of one of silicon, gallium nitride, indium phosphide, gallium arsenide, a III-Nitride material, or a III-V material.

20. The method of claim **15**, wherein the first waveguide structure is formed on a lower side of a slab of $LiNbO_3$, the lower side of the slab of $LiNbO_3$ facing the transistor.

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