APPARATUS AND METHOD TO ACHIEVE LOW LOSS PVD SINX WITH CMOS BEOL COMPATIBLE THERMAL BUDGET

BACKGROUND

Field

[0001] Certain aspects of the present disclosure generally relate to photonics. More particularly, the present disclosure provides for tools, photonic devices, device films for photonics devices, and methods of forming a device film.

Description of the Related Art

[0002] With increasing data traffic network demands, networking companies previously using traditional copper cable for communication have sought out more efficient solutions that can be deployed on a massive scale. Today, optical fiber technologies dominate the long-distance communications space. Networking companies have gradually been transitioning to using optical fibers to transmit data across shorter and shorter distances, even within clusters of devices and device to device or chip to chip. With the use of optical fibers, data is transmitted as photons at the speed of light and can be transmitted at a range of data rates, including at super-high frequencies, thereby allowing for higher data volume transmissions.

[0003] Silicon nitride is a common material used for the transportation of photons in waveguides and other photonic devices. To preserve the photonic information being transported, the silicon nitride material must have a low light propagation loss. Current deposition techniques and methods for producing low light propagation loss silicon nitride materials require high processing temperatures, often above 1,000 °C. Due to the required high processing temperatures, current methods are difficult to incorporate into the increasingly complex integration flow production of photonic devices.

[0004] There is a need for improved tools and methods for the production of low light propagation loss silicon nitride materials for the production of photonic devices.

SUMMARY

[0005] Certain aspects of the present generally relate to photonics. More particularly, the present disclosure provides for tools, photonic devices, device films for photonics devices, and methods of forming a device film.

[0006] In at least one embodiment, a photonic device is provided. The photonic device includes a substrate, a buried oxide (BOX) layer disposed over the substrate, a device layer disposed over the BOX layer, the device layer comprising at least one device, a cladding disposed over the device layer, and a lens layer disposed over the cladding, the lens layer comprising a microlens aligned with the device. At least one of the BOX layer, the device layer, the cladding, and the lens layer of the photonic device includes silicon nitride and has a propagation loss of less than about 1.5 dB/cm.

[0007] In at least one embodiment, a photonic device is provided. The photonic device includes a substrate and a film disposed on the substrate. The film includes silicon and nitrogen. The film has a thickness of about 200 nm to about 1 μm and a propagation loss of less than about 1.5 dB/cm.

[0008] In at least one embodiment, a method of forming a device film is provided. The method includes degassing a substrate in a first processing chamber, depositing a film over the substrate in a second processing chamber, the film including silicon and nitrogen, and annealing the film in a third processing chamber to form the device film. The device film has a thickness of about 200 nm to about 1 μm and a propagation loss of less than about 1.5 dB/cm.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only exemplary embodiments and are therefore not to be considered limiting of its scope, and may admit to other equally effective embodiments.

[0010] Figure 1 is a perspective view of a portion of co-packaged optical and electrical devices according to embodiments.

[0011] Figure 2 illustrates an optical arrangement according to embodiments.

[0012] Figure 3 illustrates an optical arrangement having a microlens according to embodiments.

[0013] Figure 4 is a frontal view of an optical device according to embodiments.

[0014] Figure 5 is a schematic, cross-sectional view of a portion of the optical device according to embodiments.

[0015] Figure 6 is a schematic, plan view of a cluster tool according to embodiments.

[0016] Figure 7 is a schematic, plan view of a single transfer chamber cluster tool according to embodiments.

[0017] Figure 8 is a flow diagram of a method for forming a silicon and nitrogen material containing device film according to embodiments.

[0018] To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements and features of one embodiment may be beneficially incorporated in other embodiments without further recitation.

DETAILED DESCRIPTION

[0019] Certain aspects of the present disclosure generally relate to photonics. More particularly, the present disclosure provides for tools, photonic devices, device films for photonics devices, and methods of forming a device film. It has been discovered that a silicon and nitrogen material (SiN_x) film having low light propagation loss may be produced with a low thermal budget using the tools and methods described herein. For example, using the methods described herein, SiN_x device films having a low propagation loss of less than about 1.5 dB/cm can be formed with about 400 °C to about 600 °C annealing.

[0020] Figure 1 is a perspective view of a portion of exemplary co-packaged optical and electrical devices 100 comprising an electrical or opto-electrical chip 102 connected by a plurality of optical waveguide or electrical trace interconnect 104 to a photonic integrated interconnect unit 103 where all are formed on or disposed on a package substrate 101.

[0021] In at least one embodiment, the electrical or opto-electrical chip 102 may include any high-density chip having a high I/O pin count. In some examples, the high-density chip has between 100 and 2000 I/O pins or up to (or greater than) 2000

I/O pin counts. Examples of electrical or opto-electrical chips 102 include, but are not limited to, data center SWITCH chips, artificial intelligence (AI) chips, and the like.

[0022] The photonic integrated interconnect unit 103 includes a fiber connector region configured to be coupled to a fiber connector 112 for removably connecting a fiber cable 105 to the photonic integrated interconnect unit 103. In some embodiments, the fiber cable 105 may be plugged into the fiber connector 112 to operably connect the fiber cable 105 to the co-packaged optical and electrical devices 100. In some embodiments, the photonic integrated interconnect unit 103 is configured for connecting fiber cables 105 including, but not limited to, single-mode fiber optic cables having 9 micron fiber core diameters. The fiber connector 112 may further include a plurality of optical fibers to operably connect fiber cables 105 to the photonic integrated interconnect unit 103.

[0023] In some embodiments, the photonic integrated interconnect unit 103 in the set of co-packaged electrical and optical devices is configured to transmit signals between the electrical or opto-electrical chip 102 and the fiber cable 105 connected to the photonic integrated interconnect unit 103. The photonic integrated interconnect unit 103 includes a photonic glass layer (PGL) substrate 106, a plurality of optical structures 110_1-110_N formed integral with or on the PGL substrate 106, an optical transceiver integrated circuit (SiPho chip) 108 mounted on the PGL substrate 106 and coupled to the plurality of optical structures 110_1-110_N at a first interface 107, and the fiber connector 112 connected to both the PGL substrate 106 and the plurality of optical structures 110_1-110_N at a second interface 109.

[0024] In some embodiments, the SiPho chip 108 in the photonic integrated interconnect unit 103 operates to convert electrical signals to optical signals, and vice versa. The plurality of optical structures 110_1-110_N in the photonic integrated interconnect unit 103 operate to transmit optical signals between the SiPho chip 108 and the fiber connector 112, and the optical waveguide or electrical trace interconnect 104 operate to transmit electrical or optical signals between the photonic integrated interconnect unit 103 (specifically, the SiPho chip 108) and the electrical or opto-electrical chip 102. The optical waveguide or electrical trace interconnect 104 can include metal traces that are formed within the package substrate 101, which in some embodiments can include metal traces formed in a printed circuit board (PCB) substrate or metal traces formed within a plurality of redistribution layers (e.g.,

dielectric containing layers) formed over a solid core substrate (e.g., silicon or glass core substrate).

[0025] The photonic engine may optionally further include one or more electronic phy chips 111 that are coupled to the SiPho chip 108. The electronic phy chip 111 is generally used to assist with operations performed by an optical chip. In at least one embodiment, the electronic phy chip 111 is operably connected to the SiPho chip 108 to assist the SiPho chip 108 with various electrical functions. As shown, the electronic phy chip 111 may be mounted on top of the SiPho chip 108 and thereby directly connected to the SiPho chip 108. Alternatively, the electronic phy chip 111 may be embedded in the PGL substrate 106 and connected to the SiPho chip 108 through the PGL substrate 106, which is often simply referred to herein as a substrate 106. Further, the electronic phy chip 111 can be mounted on or embedded in the package substrate 101 and connected to the SiPho chip 108 through electrical trace interconnect 104. In some embodiments, photonic integrated circuits (PICs), such as the SiPho chip 108, may include microlenses such that an optical signal may be communicated between the PICs using the microlenses, as described in more detail herein.

[0026] The co-packaged optical and electrical device 100, i.e., photonic device includes a device film. In at least one embodiment, the photonic device is a photonic device for a data center, a biosensing, or advanced computing application. The photonic device may be a waveguide. In various embodiments, the device film includes a silicon and nitrogen material (SiN_x). The SiN_x may include silicon nitride. The device film is formed using the tools and methods described herein.

[0027] Figure 2 illustrates an optical arrangement 201 according to embodiments described herein. At a first operation, an incoming device 202 is formed. The incoming device 202 includes the buried oxide (BOX) layer 204 disposed above the substrate 203. The device layer 206 is disposed on the BOX layer 204. The device layer 206 includes the device 209. The cladding 208 is disposed above the device layer 206. At a second operation, the optical arrangement 201 is formed. As shown in Figure 2, the lens layer 211 is disposed over the cladding 208. In various embodiments, the lens layer has a thickness of about 100 nm to about 1,000 um. At a third operation, as shown in Figure 3, the lens layer 211 is patterned to form the microlens 210. The microlens 210 is aligned with the device 209. The microlens 210

is implemented via the optical arrangement 201. The microlens 210 may be a microlens array 221, a Fresnel lens 223, or a flat optic 224. The flat optic 224 may be a metasurface. The microlens 210 may be made from organic liquids. In various embodiments, the microlens 210 has a diameter of about 100 nm to about 1000 um. The lens layer 211 is patterned to form the microlens 210 via photolithography, nanoimprint lithography (NIL), gray-tone lithography, e-beam lithography, etching, focused ion beam milling, ion milling, or combinations thereof. In some embodiments in which the microlenses 210 are flat optics, the second and third operations are repeated to form multiple lens layers 211 having microlenses 210. For example, a second lens layer is disposed over the lens layer 211, and a second lens is patterned in the second lens layer. The second lens is aligned with the device 209. The SiN_x containing device film may be any of the layers of the optical arrangement 301 described herein.

[0028] Figure 4 is a frontal view of an optical device 400. The optical device 400 is a waveguide combiner, such as an augmented reality waveguide combiner. The optical device 400 includes a plurality of optical device structures disposed on an optical device substrate 402. Regions of the optical device structures correspond to one or more gratings 404, such as a first grating 404a, a second grating 404b, and a third grating 404c. In some embodiments, which can combined with other embodiments described herein, the optical device 400 is a waveguide combiner that includes at least the first grating 404a corresponding to an input coupling grating and the third grating 404c corresponding to an output coupling grating. The waveguide combiner according to such embodiments, which can be combined with other embodiments described herein, includes the second grating 404b corresponding to an intermediate grating.

[0029] Figure 5 is a schematic, cross-sectional view of a portion of the optical device 400. The optical device 400 include respective optical device structures 406 disposed over a top surface of the substrate 402 in gratings. The plurality of optical device structures 406 are spaced apart from each other. The optical device structures 406 may be formed from the SiN_x containing device film described herein.

[0030] Figures 6 and 7 are schematic plan views of cluster tools that may be used to form the SiN_x containing device film described herein, according to one or more embodiments. In at least some embodiments, the cluster tools 600 and/or 700 may

be used to perform the method 800. In at least one embodiment, the method 800 for forming the SiN_x containing device film is performed using two cluster tools. In a first cluster tool, such as cluster tool 600, a substrate is subjected to a degas process 802 in a first processing chamber 602. A physical vapor deposition (PVD) process 804 is then performed to deposit the device film over the substrate in a second processing chamber 604. The substrate may optionally be cooled in the transfer chamber 606 between the degas process and the PVD process or before the substrate is removed from the first cluster tool after the PVD process. The substrate with the device film formed thereon is transferred to a second cluster tool, such as cluster tool 700, where an anneal process 806 is performed in a third processing chamber 702. In at least one embodiment, the method 800 is an in-vacuum anneal method for forming the SiN_x containing device film, performed using a single cluster tool, such as cluster tool 600. In a single cluster tool 600, the degas process 802 is performed in a first processing chamber 602, the PVD process 804 is performed in a second processing chamber 604, and the anneal process 806 is performed in a third processing camber 608 without breaking vacuum between the processes.

[0031] In at least some embodiments, the degas process 802 may be performed under ambient argon gas at a temperature of about 350 °C to about 400 °C, such as about 400 °C, and a pressure of about 3 Torr to about 10 Torr.

[0032] In at least some embodiments, the PVD process 804 may be performed at a temperature of about 350 °C to about 400 °C, such as about 400 °C, a pressure of about 6 mTorr to about 16 mTorr and a power of about 4 kW to about 10 kW. In at least some embodiments, the PVD process 804 is performed under nitrogen gas, the percent nitrogen gas may be about 70% to about 90%.

[0033] In at least some embodiments, the annealing process 806 may be performed under ambient nitrogen gas at a temperature of about 400 °C to about 700 °C, such as about 400 °C to about 600 °C, a pressure of about 300 Torr to about 760 Torr, and have a duration of about 15 minutes (min) and about 120 min, such as about 30 min to about 90 min, about 30 min to about 60 min, or about 60 min to about 90 min.

[0034] In at least one embodiment, performing the in-vacuum anneal method for forming the SiN_x containing device film in a single cluster tool increases wafer

throughput and reduces the amount of contaminant particles on the resultant SiN_x device film. The in-vacuum anneal method also prevents exposure to ambient air during the formation and annealing of the SiN_x containing device film. Ambient air may penetrate into the SiN_x grain boundaries, increasing the optical propagation loss. Preventing and/or avoiding exposure to ambient air using the disclosed in-vacuum anneal method, may result in an overall lower optical propagation loss.

[0035] Any number of additional processing steps may be performed after annealing the SiN_x containing device film. The additional processing steps may include, but are not limited to, SiN_x chemical mechanical polishing (CMP), photoresist and hard mask deposition and opening, SiN_x reactive-ion etching (RIE) etching, optional photoresist and hard mask stripping, plasma-enhanced chemical vapor deposition (PECVD) SiO_2 cladding deposition, and SiO_2 CMP. In at least one embodiment, additional processing steps include patterning the SiN_x containing device film to form devices, such as the optical device structures 406 depicted in Figure 5 or the device 209 of the device layer 206 depicted in Figure 2.

[0036] The degas process, the PVD process, and the anneal process described herein form the SiN_x device film having low light propagation loss. In at least one embodiment, the device film may have a thickness of about 200 nm to about 1 μm, such as about 200 nm to about 800 nm, about 300 nm to about 700 nm, about 300 nm to about 500 nm, or about 300 nm to about 400 nm. In at least one embodiment, the as deposited SiN_x device film may have a low propagation loss of less than about 2.5 dB/cm, such as less than about 1.5 dB/cm, less than about 1 dB/cm, or 0.8 dB/cm to about 2.5 dB/cm before the anneal process. As a non-limiting example, in at least one embodiment, an as deposited SiN_x device film having a thickness of about 700 nm had a low propagation loss of about 0.8 dB/cm. In another embodiment, an as deposited SiN_x device film having a thickness of about 350 nm had a low propagation loss of about 2.0 dB/cm. In at least one embodiment, the as deposited SiN_x device film may have a refractive index of about 2% to about 3% when measured at 633 nm, such as a refractive index of about 2.5%. In at least one embodiment, the as deposited SiN_x device film may have a stress of about -900 to about 1,000 MPa. In at least one embodiment, the as deposited SiN_x device film may have a particle adder of about 3 to about 5 when the particle size is greater than 250 nm. In at least some embodiments, after the anneal process, the SiN_x device film may have a low

propagation loss of less than about 1.5 dB/cm, such as less than about 1.3 dB/cm, less than about 1 dB/cm, or about 0.6 dB/cm to about 1.3 dB/cm. Higher temperatures and a longer duration of the anneal process may result in SiN_x device films having lower propagation loss. As a non-limiting example, in one embodiment a SiN_x device film annealed for 60 min at about 400 °C had a low propagation loss of about 1.13 dB/cm. In contrast, a SiN_x device film annealed for 60 min at about 600 °C had a low propagation loss of about 0.61 dB/cm (e.g., about 0.6 dB/cm). In one embodiment, a SiN_x device film annealed at about 400 °C for 30 min had a low propagation loss of about 1.23 dB/cm; in contrast, a film annealed at about 400 °C for 90 min had a low propagation loss of about 1.11 dB/cm (e.g., about 1.1 dB/cm).

[0037] In at least some embodiments, the disclosed SiN_x device film is used in neuromorphic photonic computing, photonic quantum computing, and/or optical quantum computing. In at least one embodiment, the SiN_x device film may be the device film of a waveguide in a neuromorphic photonic computing device having a propagation loss of less than about 1 dB/cm. In at least one embodiment, the SiN_x device film may be the device film of a waveguide of a quantum information processing part in a photonic quantum computing device having a propagation loss of less than about 0.1 dB/cm. In at least one embodiment, the SiNx device film may be the device film of a waveguide of a non-quantum information processing part in a photonic quantum computing device having a propagation loss of less than about 1 dB/cm.

[0038] Overall, tools, photonic devices, low propagation loss device films for photonics devices, and methods of forming a low propagation loss device film are shown and described herein. SiN_x device films having a low propagation loss of less than about 1.5 dB/cm may be achieved with an annealing temperature of about 400 °C to about 600 °C. The low thermal budget of the post deposition anneal process is compatible with complementary metal-oxide-semiconductor (CMOS) back end of the line (BEOL) processes, allowing for easy incorporation of the disclosed methods into the increasingly complex integration flow production of photonic devices.

[0039] While the foregoing is directed to examples of the present disclosure, other and further examples of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. A photonic device comprising:

a substrate;

a buried oxide (BOX) layer disposed over the substrate;

a device layer disposed over the BOX layer, the device layer comprising at least one device;

a cladding disposed over the device layer; and

a lens layer disposed over the cladding, the lens layer comprising a microlens aligned with the device, wherein at least one of the BOX layer, the device layer, the cladding, and the lens layer comprises silicon nitride and has a propagation loss of less than about 1.5 dB/cm.

2. The photonic device of claim 1, wherein the photonic device is a photonic data center device, a biosensing device, or a computing device.

3. The photonic device of claim 1, wherein the photonic device is a waveguide.

4. The photonic device of claim 3, wherein at least one of the BOX layer, the device layer, the cladding, and the lens layer comprises silicon nitride and has a thickness of about 200 nm to about 1μm.

5. The photonic device of claim 1, wherein the device layer comprises silicon nitride and has a propagation loss of about 0.6 dB/cm to about 1.3 dB/cm.

6. The photonic device of claim 1, wherein the lens layer comprises silicon nitride and has a propagation loss of about 0.6 dB/cm to about 1.3 dB/cm.

7. A photonic device comprising:

a substrate; and

a film disposed on the substrate, the film comprising silicon and nitrogen, the film having a thickness of about 200 nm to about 1 μm and a propagation loss of less than about 1.5 dB/cm.

8. The photonic device of claim 7, wherein the film comprises silicon nitride.

9. The photonic device of claim 7, wherein the film has a propagation loss of about 0.6 dB/cm to about 1.3 dB/cm.

10. The photonic device of claim 7, wherein the film has a propagation loss of less than about 1.1 dB/cm.

11. A method of forming a device film comprising:

degassing a substrate in a first processing chamber;

depositing a film over the substrate in a second processing chamber, the film comprising silicon and nitrogen; and

annealing the film in a third processing chamber to form the device film, the device film having a thickness of about 200 nm to about 1 μm and a propagation loss of less than about 1.5 dB/cm.

12. The method of claim 11, wherein the first processing chamber, the second processing chamber, and the third processing chamber are included in a first cluster tool.

13. The method of claim 11, wherein the first processing chamber and the second processing chamber are included in a first cluster tool, and the third processing chamber is included in a second cluster tool.

14. The method of claim 11, wherein the film is deposited using a physical vapor deposition (PVD) process.

15. The method of claim 11, wherein the film is annealed at a temperature of about 400 °C to about 600 °C.

16. The method of claim 11, wherein the film is annealed for about 15 minutes to about 120 minutes.

17. The method of claim 11, wherein the film is annealed at a temperature of about 400 °C and the device film has a propagation loss of about 1.1 dB/cm to about 1.2 dB/cm.

18. The method of claim 11, wherein the device film comprises silicon nitride.

19. The method of claim 11, wherein the film has a propagation loss of about 0.8 dB/cm to about 2.5 dB/cm.

20. The method of claim 11, wherein the film is annealed at a temperature of about 600 °C and the device film has a propagation loss of about 0.6 dB/cm.