

Description

Technical Field

The invention is concerned with devices including a substrate-supported waveguide as may be used, e.g., in optical communications systems.

Background of the Invention

As optical communications are gaining entry into the fields of subscriber-loop and local-area networks, increased attention is being paid to the feasibility of substrate-supported waveguides as forming predefined optical paths in couplers and between optical component devices such as, e.g., light sources and detectors on a common substrate. Considered as eminently desirable in this respect are means for forming low-loss waveguides which are suitable for side-by-side coupling.

One arrangement for fabricating substrate-supported waveguides is discussed in an article entitled "Ring Resonator Fabricated in Phosphosilicate Glass Films Deposited by Chemical Vapor Deposition" by A. Naumaan et al. appearing in the *Journal of Lightwave Technology*, Vol. LT-4, No. 9, September 1986 at pp. 1294 et seq. In particular, Naumaan et al. describe a method of forming waveguides by covering a silicon wafer with a first layer of thermal oxide, followed by a layer of deposited oxide, which is in turn covered with phosphosilicate glass. The laminate is then etched and heated to form the desired structure, the etched phosphosilicate layer thus forming a waveguide.

According to the present invention there is provided a method as defined in claim 1 or 2.

In the manufacture of optical devices and assemblies, substrate-supported waveguides are provided for the transmission of one or, possibly, several optical modes. Preferred optical waveguides comprise a core portion on a first cladding layer, and such waveguides have a smoothed surface or core-cladding interface with an overlying second cladding layer. Furthermore, by inclusion of a core-cladding wetting layer, a preferred core profile provides for smooth transition, without re-entrant corners, between the core and the first cladding layer. Resulting waveguides can be made in close-spaced side-by-side relationship as is desirable for lateral (evanescent-field) coupling between waveguides.

Brief Description of the Drawing

FIG. 1 is a schematic top view of an optical coupler as a preferred embodiment of the invention, including side-by-side substrate-supported

waveguides; and

FIG. 2 is a schematic cross-sectional view of the coupler of FIG. 1.

Detailed Description

FIG. 1 shows glass-covered silicon substrate 11, substrate-supported waveguide cores 12 and 13 (between first and second cladding layers as shown in FIG. 2), and optical fibers 14, 15, 16 and 17 aligned with waveguides 12 and 13.

FIG. 2 shows substrate 11, first waveguide cladding layer 21 on substrate 11, waveguide cores 12 and 13 on layer 21, wetting layer 22, and second cladding layer 23.

Other than silicon, materials such as, e.g., Group III-V semiconductor materials can serve as substrate materials; similarly, insulating materials such as, e.g., fused silica or ceramic materials can be used. First waveguide cladding layer 21 may be as deposited or as obtained by substrate-surface reaction; for example, in the case of a silicon substrate, layer 21 may be a "thermally grown" silicon dioxide layer as obtained by thermal oxidation of substrate surface material. (Such oxidation is favored under steam at elevated pressure.)

The material of waveguides 12 and 13 has a refractive index which, for waveguiding purposes, is higher than the refractive index of the material of layer 21. For example, when layer 21 consists essentially of silicon dioxide, the material of waveguides 12 and 13 may be a doped silica-based glass such as, e.g., phosphosilicate glass as obtained by including phosphorus pentoxide as a dopant. Among alternative dopants are germania and titanium dioxide; also, there are many suitable combinations including more than one dopant. Where substrate-supported waveguides are to be coupled to optical fibers, waveguide width and height preferably are approximately the same; for a preferred way of aligning fibers with waveguides see the patent application designated as G. E. Blonder 10, "Device Including a Component in Alignment with a Substrate-supported Waveguide".

The material of second cladding layer 23 has a refractive index which is less than the refractive index of the waveguide core material; conveniently, the material of layer 23 may be the same as the material of layer 21. Also, layer 23 may be omitted, with air serving as low-index material vis-a-vis the waveguide core material.

For optical radiation at a wavelength at or near 1.3 micrometer (as understood to represent an approximate range from 1.2 to 1.6 micrometer), the following dimensions and materials are preferred: A silicon substrate; a silicon dioxide first cladding layer having a thickness of 10 to 15 micrometers, a phosphosilicate waveguide approximately 5 mi-

rometers wide and 5 micrometers thick, and a silica glass second cladding layer approximately 5 micrometers thick. For other wavelengths, and especially for shorter wavelengths, dimensions may require adjustment in the interest of limitation to a desired number of optical modes. Preferred phosphosilicate glass comprises phosphorus in an amount in the range from 6 to 8 weight percent, glasses with less than 6 weight percent phosphorus having a tendency to crack, and glasses with more than 8 weight percent phosphorus tending to be hygroscopic.

Manufacture of a preferred waveguide structure involves deposition of a layer of waveguide core glass on the first cladding layer, deposition of a photolithographic resist layer on the core glass, patterning of the resist layer so as to uncover portions of core glass to be removed, removal of uncovered core glass, application of a core-cladding wetting agent, smoothing and cross-sectional rounding of the waveguide by heating, and deposition of the second cladding layer. Conveniently, deposition of core and cladding glasses may be by chemical vapor deposition, using precursor gases such as, e.g., silane, TEOS, or DABS for silica, and phosphine for phosphorus pentoxide.

Preferably, in the interest of positive control over etched waveguide thickness, a tri-level photolithographic mask layer is used, including, e.g., a plasma-deposited silica layer between two organic resist layers. Core glass exposed after photolithographic patterning of the mask layer may be removed, e.g., by chemical or reactive-ion etching, and such etching may typically result also in the removal of a small portion of the first cladding material. As etched, waveguide cross-sectional profile is essentially square or rectangular.

After waveguide etching, and prior to second cladding deposition, a waveguide smoothing step is included for the sake of longitudinal as well cross-sectional smoothing of the waveguide surface, and of cross-sectional rounding of the waveguide. In the interest of preventing re-entrant corners between the waveguide and the first cladding layer, such smoothing is carried out after deposition of a wetting agent on the patterned waveguide; conveniently, the material of this layer is essentially the same as the waveguide core material.

As an alternative to deposition of waveguide core material for the purpose of forming a wetting layer, it may be possible to control waveguide etching so as to produce a wetting layer as a residual layer of waveguide core material on the underlying first cladding layer. In either case, the thickness of a wetting layer whose refractive index matches the refractive index of the waveguide core material preferably is limited in the interest of lateral confinement of radiation traveling in the result-

ing waveguide, and of minimization of loss to the substrate. In this respect, preferred wetting layer thickness as incorporated in the waveguide structure is less than 1 micrometer, and preferably less than 0.5 micrometer.

Preferred smoothing serves to reduce processing-induced waveguide surface roughness and waviness, both of which bear directly on optical loss in waveguide use. Also, smoothing may further serve for densifying the waveguide core glass by permitting accidentally trapped gases to escape, thereby contributing to loss reduction.

Smoothing and densifying may be accomplished by raising the temperature of the waveguide material above its flow temperature, e.g., in a steam atmosphere. (Flow temperature is related to glass transition temperature; e.g., for phosphosilicate glasses, flow temperature is approximately 300 °C above the glass transition temperature. For further details in this respect see K. Nassau et al., "Modified Phosphosilicate Glasses for VLSI Applications". *Journal of the Electrochemical Society*, Vol. 132(1985), pp. 409-415.) Also, depending on waveguide material, care is indicated so as to assure that temperature remain below a critical temperature - beyond which waveguide transparency may be affected adversely as due, e.g., to phase separation. For example, in the case of phosphosilicate glass containing 6-8 weight percent phosphorus, temperature preferably is limited to temperatures not significantly exceeding a temperature of approximately 1100 °C. Following heat treatment, waveguide core glass is cooled.

On account of smooth contours and absence of re-entrant corners between waveguide core and cladding, waveguides of the invention are particularly suitable in the manufacture of evanescent-field couplers as may be included in optical communications systems. Furthermore, in such systems, waveguides of the invention can serve for the optical interconnection of substrate-supported light sources and detectors, e.g., in two-way transmission through a common port, in star couplers, and for filters, reflectors, and resonators, e.g., in local-area network applications. (Filters, reflectors, resonators, and the like may involve the localized incorporation of diffraction gratings, e.g., at the interface between the first cladding layer and the waveguide core, or at the interface between the waveguide core and the second cladding layer.)

Among other devices contemplated are resonant ring gyroscopes where low loss in substrate-supported waveguides is particularly desirable.

Example

On a 10-centimeter silicon substrate having a thickness of approximately 0.5 millimeter, a 10-micrometer layer of silicon dioxide was grown by high-pressure oxidation under steam. On the grown layer, an additional 5-micrometer layer of silica glass was deposited by standard low-pressure chemical vapor deposition (LPCVD), using silane and oxygen at a temperature of approximately 400 °C and a pressure of approximately 0.5 Torr (67

a).

On the silica layer, a phosphosilicate glass layer was deposited by the same method, further using phosphine. Phosphorus content of the deposited glass was approximately 6.5 percent by weight, and layer thickness was approximately 4 micrometers. The deposited phosphosilicate glass was densified at a temperature of approximately 1000 °C for 60 minutes in flowing nitrogen.

A 6-centimeter waveguide was etched out of the deposited phosphosilicate layer by reactive-ion etching (RIE) in the presence of a patterned tri-level mask consisting, as deposited, of a bottom layer of organic resist material approximately 3 micrometers thick, an intermediate layer of plasma-deposited silicon dioxide approximately 0.24 micrometer thick, and an organic top layer approximately 0.7 micrometer thick. As etched, waveguide width was approximately 6 micrometers.

On the etched waveguide, a 0.3-micrometer layer of phosphosilicate glass of the same composition as the core material was deposited as a wetting layer, and the resulting structure was smoothed by heating at a temperature of approximately 1100 °C for 60 minutes in flowing nitrogen. On the smoothed waveguide a 5-micrometer layer of undoped silica was deposited by low-pressure chemical vapor deposition under conditions as described above, and the deposited silica layer was densified by heating at a temperature of approximately 1000 °C.

Optical loss of the waveguide was experimentally determined for 1.3-micrometer radiation; total loss, including butt-coupling input and output losses, was found to be approximately 1.2 dB. Accordingly, loss per unit length of the waveguide was less than 0.2 dB/cm.

Claims

1. A method of making a device comprising a substrate-supported waveguide, said method comprising the steps of:

- (a) forming a waveguide cladding layer (21) over a top major surface of a substrate (11),
- (b) depositing a layer of waveguide core material (12) over said waveguide cladding

layer,

(c) selectively removing portions of said layer of core material to produce a pattern comprising said waveguide,

(d) depositing a wetting layer (22) on said remaining core material and at least a portion of said waveguide cladding layer adjacent to said core material, and

(e) smoothing said waveguide by heating and thereby melting the wetting layer.

2. A method of making a device comprising a substrate-supported waveguide, said method comprising the steps of:

- (a) forming a waveguide cladding layer (21) over a top major surface of a substrate (11),
- (b) depositing a layer of waveguide core material (12) over said waveguide cladding layer,

(c) selectively removing portions of said layer of core material to produce a pattern comprising said waveguide,

(d) providing a residual layer of core material as a wetting layer (22) on said remaining core material and at least a portion of said waveguide cladding layer adjacent to said core material, and

(e) smoothing said waveguide by heating and thereby melting the wetting layer.

3. A method of making a device as defined in claim 1 wherein step (d), utilizes a wetting layer having a material which is essentially the same as the material of said waveguide core.

4. A method of making a device as defined in claims 1 or 2 wherein in the forming step (a), the waveguide cladding layer is deposited on a body of silicon.

5. A method of making a device as defined in claims 1 or 2 wherein in the forming step (a), a layer of silicon dioxide is deposited as the waveguide cladding layer.

6. A method of making a device as defined in claims 1 or 2 wherein in the deposition step (b) a layer of phosphosilicate glass is deposited.

7. A method of making a device as defined in claims 1 or 2 wherein in forming step (a), a ceramic substrate is provided.

8. A method of making a device as defined in claim 7 wherein the ceramic is fused silica.

9. A method of making a device as defined in claims 1 or 2 wherein the method comprises



Example

On a 10-centimeter silicon substrate having a thickness of approximately 0.5 millimeter, a 10-micrometer layer of silicon dioxide was grown by high-pressure oxidation under steam. On the grown layer, an additional 5-micrometer layer of silica glass was deposited by standard low-pressure chemical vapor deposition (LPCVD), using silane and oxygen at a temperature of approximately 400 °C and a pressure of approximately 0.5 Torr (67²a).

On the silica layer, a phosphosilicate glass layer was deposited by the same method, further using phosphine. Phosphorus content of the deposited glass was approximately 6.5 percent by weight, and layer thickness was approximately 4 micrometers. The deposited phosphosilicate glass was densified at a temperature of approximately 100 °C for 60 minutes in flowing nitrogen.

A 6-centimeter waveguide was etched out of the deposited phosphosilicate layer by reactive-ion etching (RIE) in the presence of a patterned tri-level mask consisting, as deposited, of a bottom layer of organic resist material approximately 3 micrometers thick, an intermediate layer of plasma-deposited silicon dioxide approximately 0.24 micrometer thick, and an organic top layer approximately 0.7 micrometer thick. As etched, waveguide width was approximately 6 micrometers.

On the etched waveguide, a 0.3-micrometer layer of phosphosilicate glass of the same composition as the core material was deposited as a wetting layer, and the resulting structure was smoothed by heating at a temperature of approximately 1100 °C for 60 minutes in flowing nitrogen. On the smoothed waveguide a 5-micrometer layer of undoped silica was deposited by low-pressure chemical vapor deposition under conditions as described above, and the deposited silica layer was densified by heating at a temperature of approximately 1000 °C.

Optical loss of the waveguide was experimentally determined for 1.3-micrometer radiation; total loss, including butt-coupling input and output losses, was found to be approximately 1.2 dB. Accordingly, loss per unit length of the waveguide was less than 0.2 dB/cm.

Claims

1. A method of making a device comprising a substrate-supported waveguide, said method comprising the steps of:
 - (a) forming a waveguide cladding layer (21) over a top major surface of a substrate (11),
 - (b) depositing a layer of waveguide core material (12) over said waveguide cladding

layer,

(c) selectively removing portions of said layer of core material to produce a pattern comprising said waveguide,

(d) depositing a wetting layer (22) on said remaining core material and at least a portion of said waveguide cladding layer adjacent to said core material, and

(e) smoothing said waveguide by heating and thereby melting the wetting layer.

2. A method of making a device comprising a substrate-supported waveguide, said method comprising the steps of:

(a) forming a waveguide cladding layer (21) over a top major surface of a substrate (11),
 (b) depositing a layer of waveguide core material (12) over said waveguide cladding layer,

(c) selectively removing portions of said layer of core material to produce a pattern comprising said waveguide,

(d) providing a residual layer of core material as a wetting layer (22) on said remaining core material and at least a portion of said waveguide cladding layer adjacent to said core material, and

(e) smoothing said waveguide by heating and thereby melting the wetting layer.

3. A method of making a device as defined in claim 1 wherein step (d), utilizes a wetting layer having a material which is essentially the same as the material of said waveguide core.

4. A method of making a device as defined in claims 1 or 2 wherein in the forming step (a), the waveguide cladding layer is deposited on a body of silicon.

5. A method of making a device as defined in claims 1 or 2 wherein in the forming step (a), a layer of silicon dioxide is deposited as the waveguide cladding layer.

6. A method of making a device as defined in claims 1 or 2 wherein in the deposition step (b) a layer of phosphosilicate glass is deposited.

7. A method of making a device as defined in claims 1 or 2 wherein in forming step (a), a ceramic substrate is provided.

8. A method of making a device as defined in claim 7 wherein the ceramic is fused silica.

9. A method of making a device as defined in claims 1 or 2 wherein the method comprises



the further step of:

(f) depositing an outer waveguide cladding layer over the wetting layer.

10. A method of making a device as defined in claim 9 wherein in the deposition step (f) a layer of silica is deposited.

Patentansprüche

1. Verfahren zur Herstellung einer Einrichtung mit einem substratgetragenen Wellenleiter, wobei das Verfahren die Schritte enthält:

(a) Bilden einer Wellenleiter-Mantelschicht (21) über einer Hauptoberfläche eines Substrats (11),

(b) Abscheiden einer Schicht des Wellenleiter-Kernmaterials (12) über der Wellenleiter-Mantelschicht,

(c) selektives Entfernen von Anteilen der Schicht aus Kernmaterial, um ein Muster zu erzeugen, das den Wellenleiter enthält,

(d) Abscheiden einer benetzenden Schicht (22) auf dem verbleibenden Kernmaterial und wenigstens einem Teil der dem Kernmaterial benachbarten Wellenleiter-Mantelschicht und

(e) Glätten des Wellenleiters durch Erhitzen und dadurch Schmelzen der benetzenden Schicht.

2. Verfahren zur Herstellung einer Einrichtung mit einem substratgetragenen Wellenleiter, wobei das Verfahren die Schritte enthält:

(a) Bilden einer Wellenleiter-Mantelschicht (21) über einer Hauptoberfläche eines Substrats (11),

(b) Abscheiden einer Schicht aus Wellenleiter-Kernmaterial (12) über der Wellenleiter-Mantelschicht,

(c) selektives Entfernen von Anteilen der Schicht aus Kernmaterial, um ein den Wellenleiter enthaltendes Muster zu erzeugen,

(d) Bereitstellen einer zurückgebliebenen Schicht auf dem Kernmaterial als benetzende Schicht (22) auf dem verbleibenden Kernmaterial und auf wenigstens einem Teil der Wellenleiter-Mantelschicht in der Nähe des Kernmaterials und

(e) Glätten des Wellenleiters durch Erhitzen und dadurch Schmelzen der benetzenden Schicht.

3. Verfahren zur Herstellung einer Einrichtung gemäß Anspruch 1, in welchem der Schritt (d) eine benetzende Schicht mit einem Material, das im wesentlichen das gleiche wie das Material des Wellenleiterkerns ist, verwendet.

4. Verfahren zur Herstellung einer Einrichtung nach Anspruch 1 oder 2, in welchem der Formungsschritt (a) umfaßt, daß die Wellenleiter-Mantelschicht auf einem Siliziumkörper abgeschieden wird.

5. Verfahren zur Herstellung einer Einrichtung nach Anspruch 1 oder 2, in welchem der Formungsschritt (a) umfaßt, daß eine Schicht aus Siliciumdioxid als Wellenleiter-Mantelschicht abgeschieden wird.

6. Verfahren zur Herstellung einer Einrichtung nach Anspruch 1 oder 2, in welchem der Abscheidungsschritt (b) umfaßt, daß eine Schicht aus Phosphorsilikatglas abgeschieden wird.

7. Verfahren zur Herstellung einer Einrichtung nach Anspruch 1 oder 2, in welchem der Formungsschritt (a) umfaßt, daß ein keramisches Substrat bereitgestellt wird.

8. Verfahren zur Herstellung einer Einrichtung nach Anspruch 7, in welchem die Keramik geschmolzenes Silikatglas ist.

9. Verfahren zur Herstellung einer Einrichtung nach Anspruch 1 oder 2, in welchem das Verfahren ferner den Schritt umfaßt:

(f) Abscheiden einer äußeren Wellenleiter-Mantelschicht über der benetzenden Schicht.

10. Verfahren zur Herstellung einer Einrichtung nach Anspruch 9, in welchem der Abscheidungsschritt (f) umfaßt, daß eine Schicht aus Silikatglas abgeschieden wird.

Revendications

1. Un procédé de fabrication d'un dispositif comprenant un guide d'ondes supporté par un substrat, ce procédé comprenant les étapes suivantes :

(a) on forme une couche de gaine de guide d'ondes (21) sur une surface principale supérieure d'un substrat (11);

(b) on dépose une couche de matériau de cœur de guide d'ondes (12) sur la couche de gaine de guide d'ondes,

(c) on enlève sélectivement des parties de la couche de matériau de cœur pour former un motif constituant le guide d'ondes,

(d) on dépose une couche de mouillage (22) sur le matériau de cœur restant et sur au moins une partie de la couche de gaine de guide d'ondes adjacente au matériau de cœur, et



- (e) on lisse le guide d'ondes en chauffant et en faisant ainsi fondre la couche de mouillage.
2. Un procédé de fabrication d'un dispositif comprenant un guide d'ondes supporté par un substrat, ce procédé comprenant les étapes suivantes :
- (a) on forme une couche de gaine de guide d'ondes (21) sur une surface principale supérieure d'un substrat (11);
- (b) on dépose une couche de matériau de coeur de guide d'ondes (12) sur la couche de gaine de guide d'ondes,
- (c) on enlève sélectivement des parties de la couche de matériau de coeur pour former un motif constituant le guide d'ondes,
- (d) on forme une couche résiduelle de matériau de coeur, à titre de couche de mouillage (22) sur le matériau de coeur restant et sur au moins une partie de la couche de gaine de guide d'ondes adjacente au matériau de coeur, et
- (e) on lisse le guide d'ondes en chauffant et en faisant ainsi fondre la couche de mouillage.
3. Un procédé de fabrication d'un dispositif selon la revendication 1, dans lequel l'étape (d) utilise une couche de mouillage constituée par un matériau qui est fondamentalement identique au matériau de coeur de guide d'ondes.
4. Un procédé de fabrication d'un dispositif selon les revendications 1 ou 2, dans lequel au cours de l'étape de formation (a), on dépose la couche de gaine de guide d'ondes sur un bloc de silicium.
5. Un procédé de fabrication d'un dispositif selon les revendications 1 ou 2, dans lequel au cours de l'étape de formation (a), on dépose une couche de dioxyde de silicium pour la couche de gaine de guide d'ondes.
6. Un procédé de fabrication d'un dispositif selon les revendications 1 ou 2, dans lequel au cours de l'étape de dépôt (b), on dépose une couche de verre au phosphosilicate.
7. Un procédé de fabrication d'un dispositif selon les revendications 1 ou 2, dans lequel au cours de l'étape de formation (a), on utilise un substrat en céramique.
8. Un procédé de fabrication d'un dispositif selon la revendication 7, dans lequel la céramique est de la silice fondue.
9. Un procédé de fabrication d'un dispositif selon les revendications 1 ou 2, dans lequel le procédé comprend l'étape supplémentaire suivante :
- (f) on dépose une couche de gaine de guide d'ondes extérieure sur la couche de mouillage.
10. Un procédé de fabrication d'un dispositif selon la revendication 9, dans lequel au cours de l'étape de dépôt (f), on dépose une couche de silice.