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(54) **WAFER SCALE MONOLITHIC INTEGRATION OF LASERS, MODULATORS, AND OTHER OPTICAL COMPONENTS USING ALD OPTICAL COATINGS**

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H01S 5/02	(2006.01)
H01S 5/028	(2006.01)

(52) **U.S. Cl.**
CPC ***H01S 5/021*** (2013.01); ***H01S 5/0265*** (2013.01); ***H01S 5/0287*** (2013.01); *H01S 2301/176* (2013.01)

(58) **Field of Classification Search**
CPC H01S 5/021; H01S 5/0265; H01S 5/0287
See application file for complete search history.

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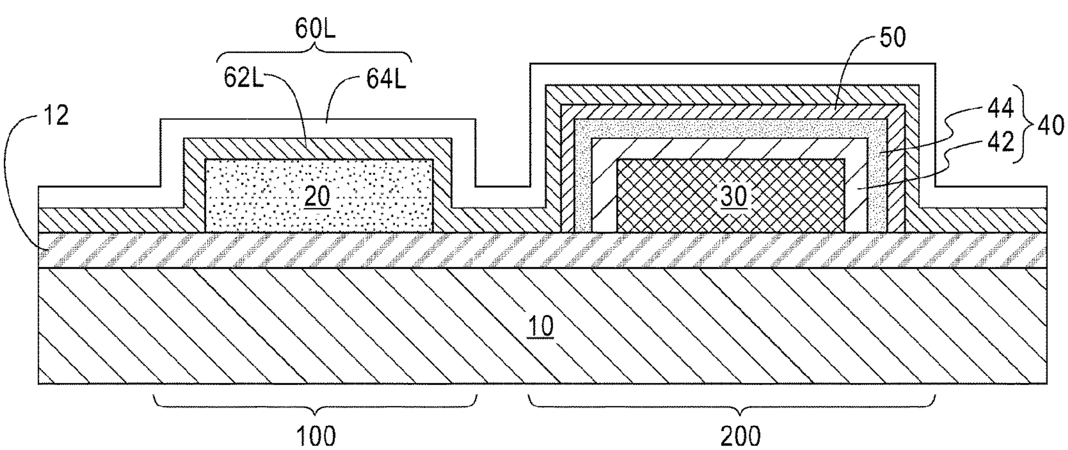
(57) **ABSTRACT**

After forming a monolithically integrated device including a laser and a modulator on a semiconductor substrate, an anti-reflection coating layer is formed over the monolithically integrated device and the semiconductor substrate by an atomic layer deposition (ALD) process. The anti-reflection coating layer is lithographically patterned so that an anti-reflection coating is only present on exposed surfaces of the modulator. After forming an etch stop layer portion to protect the anti-reflection coating, a high reflection coating layer is formed over the etch stop layer, the laser and the semiconductor structure by ALD and lithographically patterned to provide a high reflection coating that is formed solely on a non-output facet of the laser.

17 Claims, 9 Drawing Sheets



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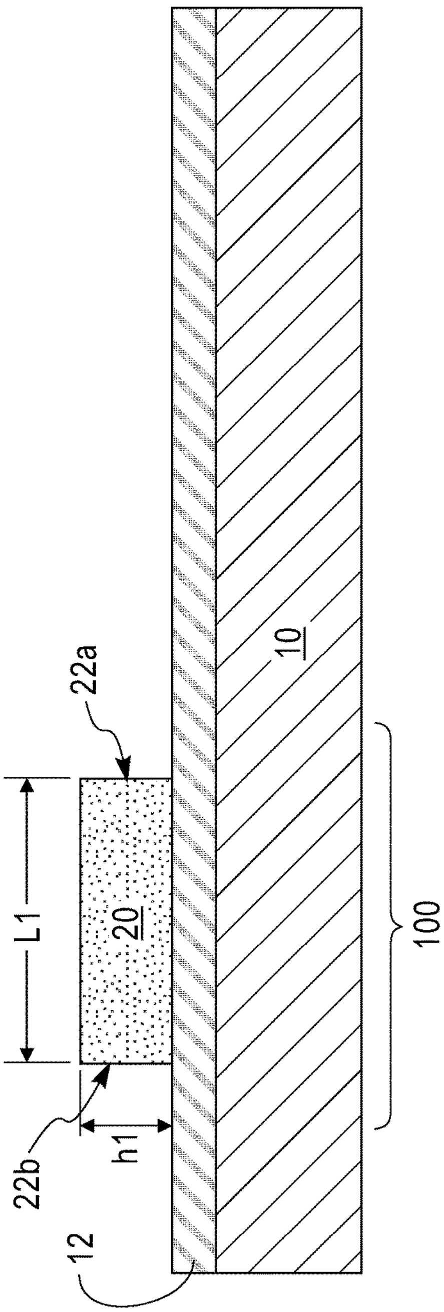

FIG. 1

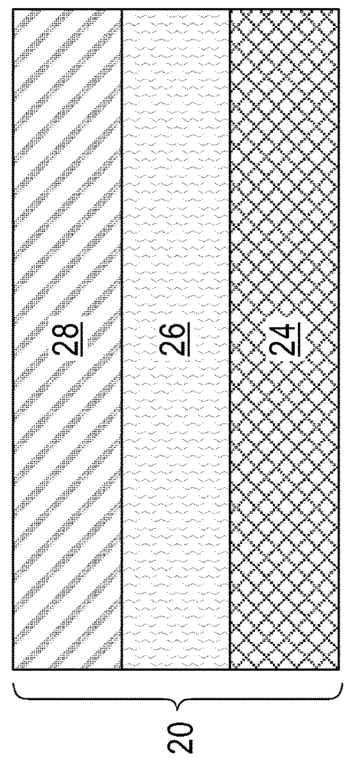

FIG. 2

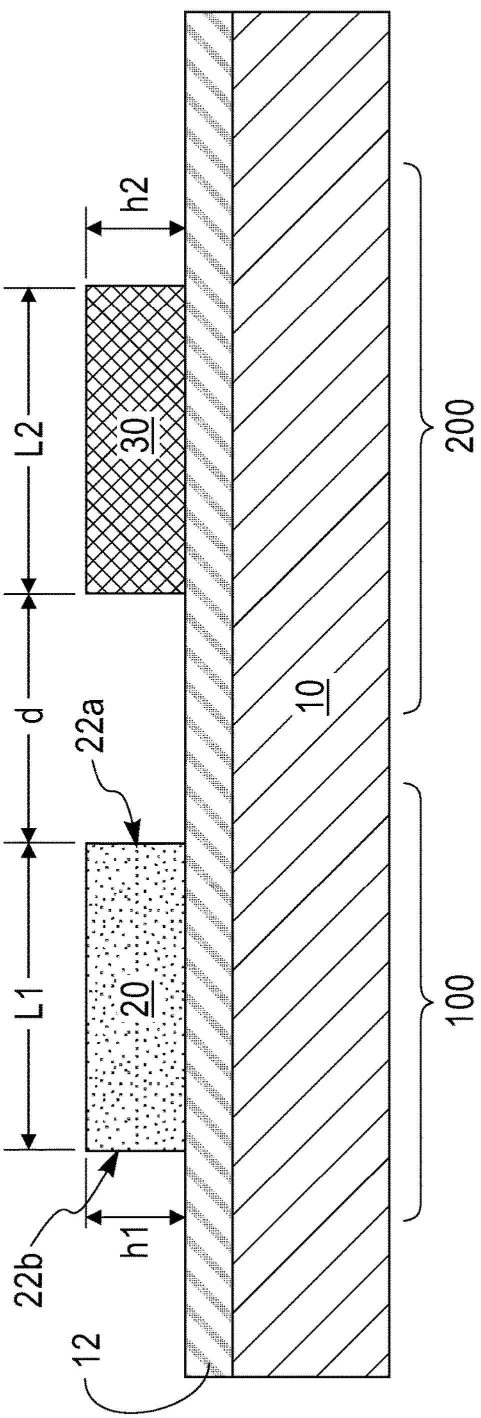

FIG. 3

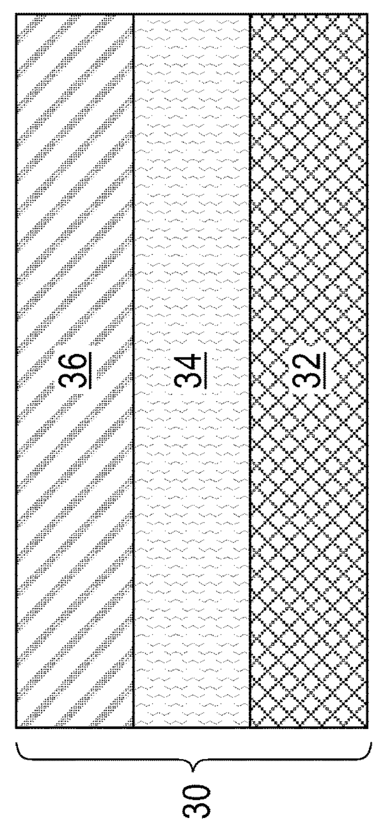

FIG. 4

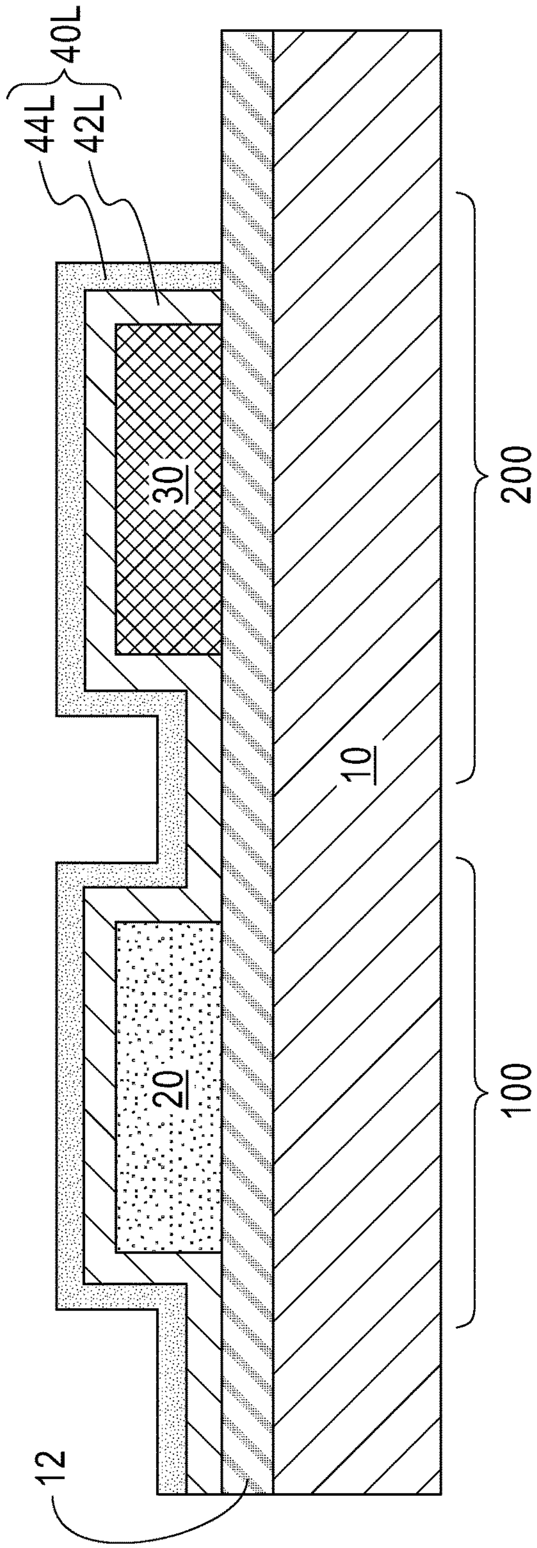

FIG. 5

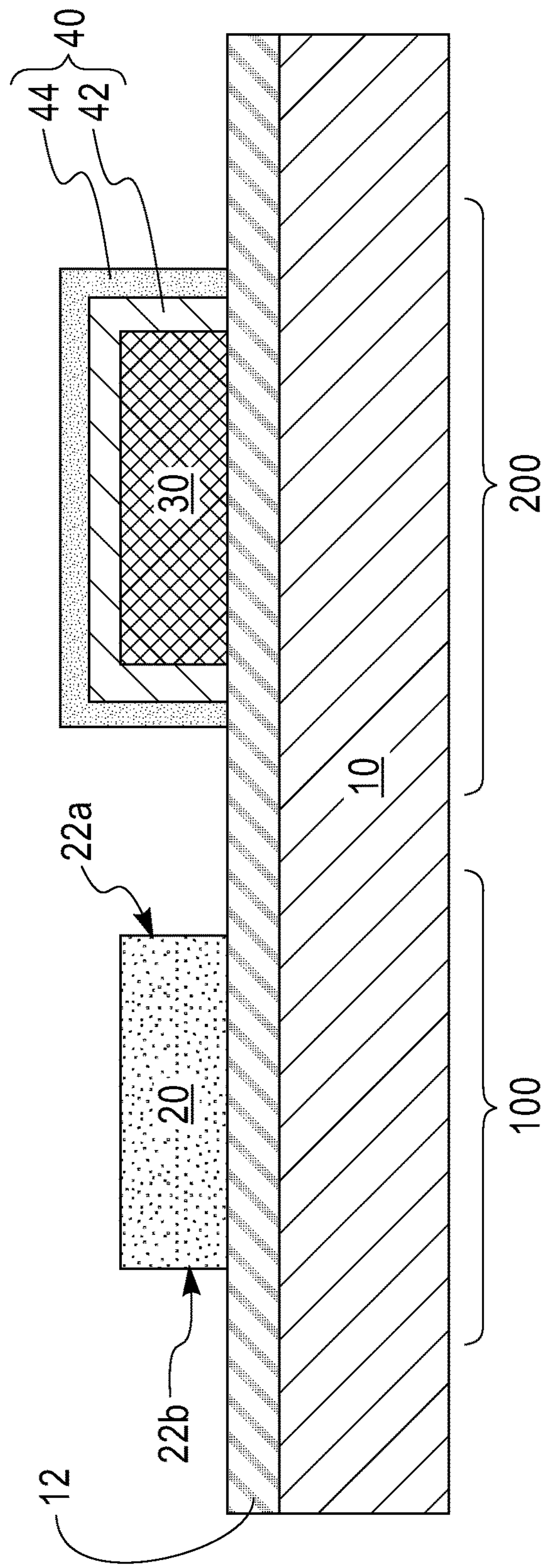

FIG. 6

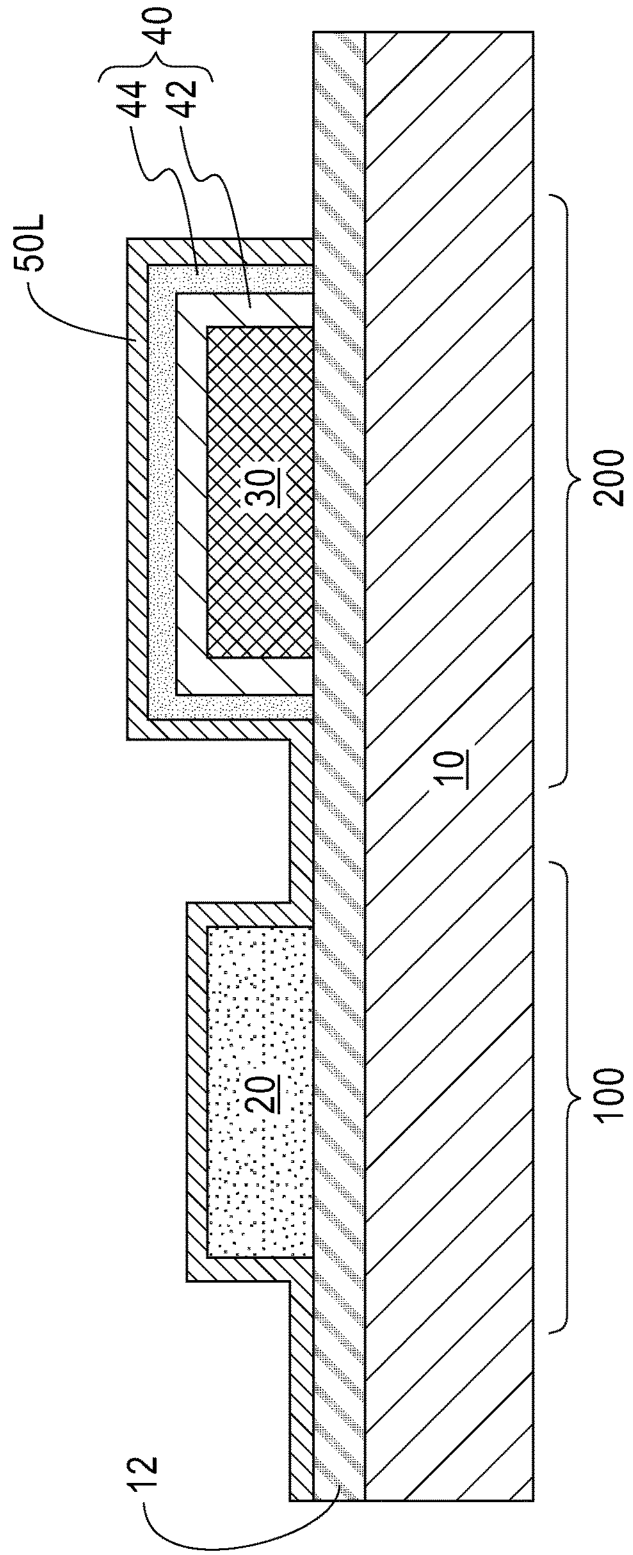

FIG. 7

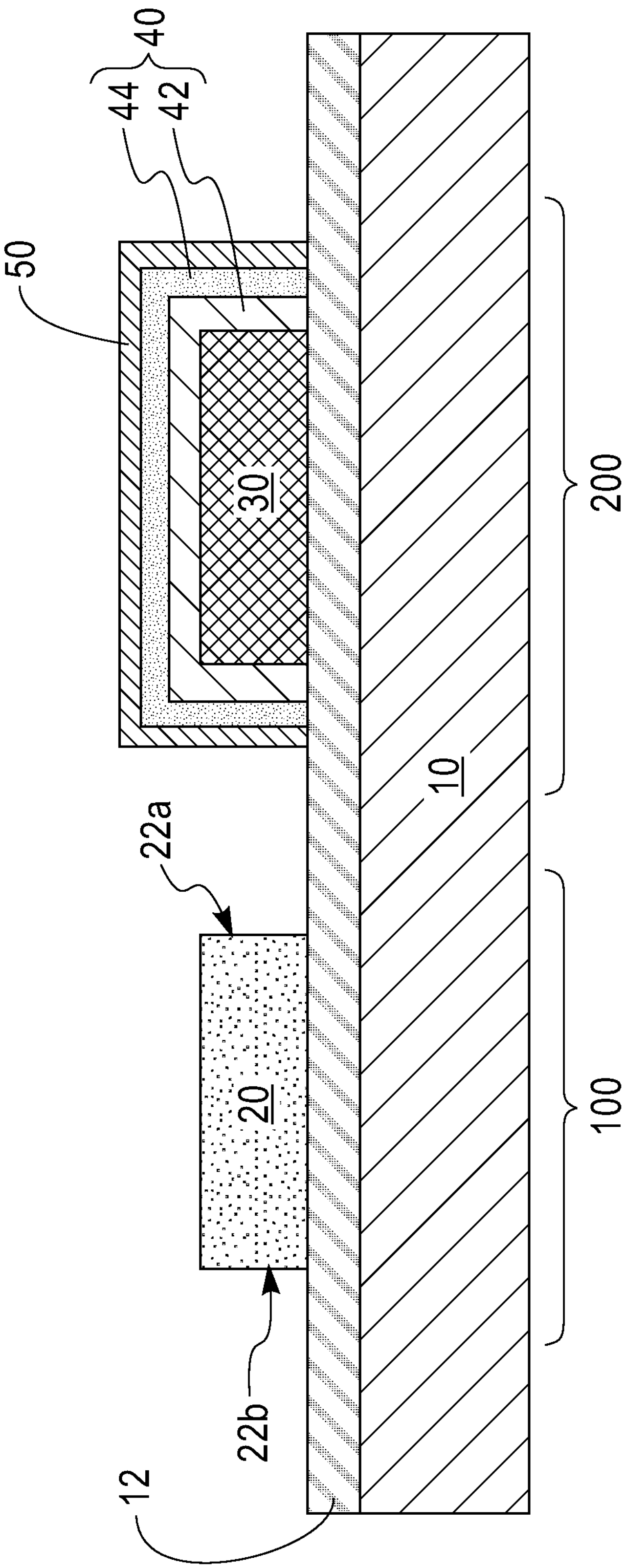

FIG. 8

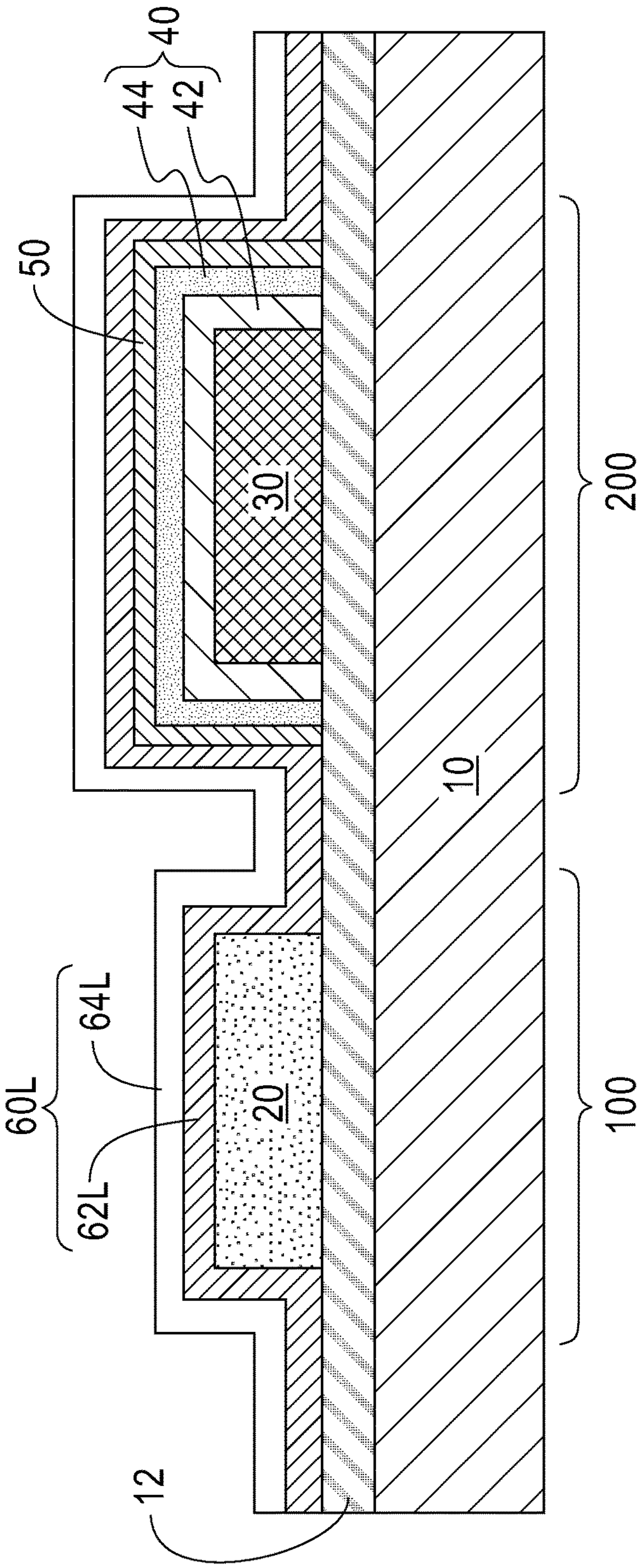

FIG. 9

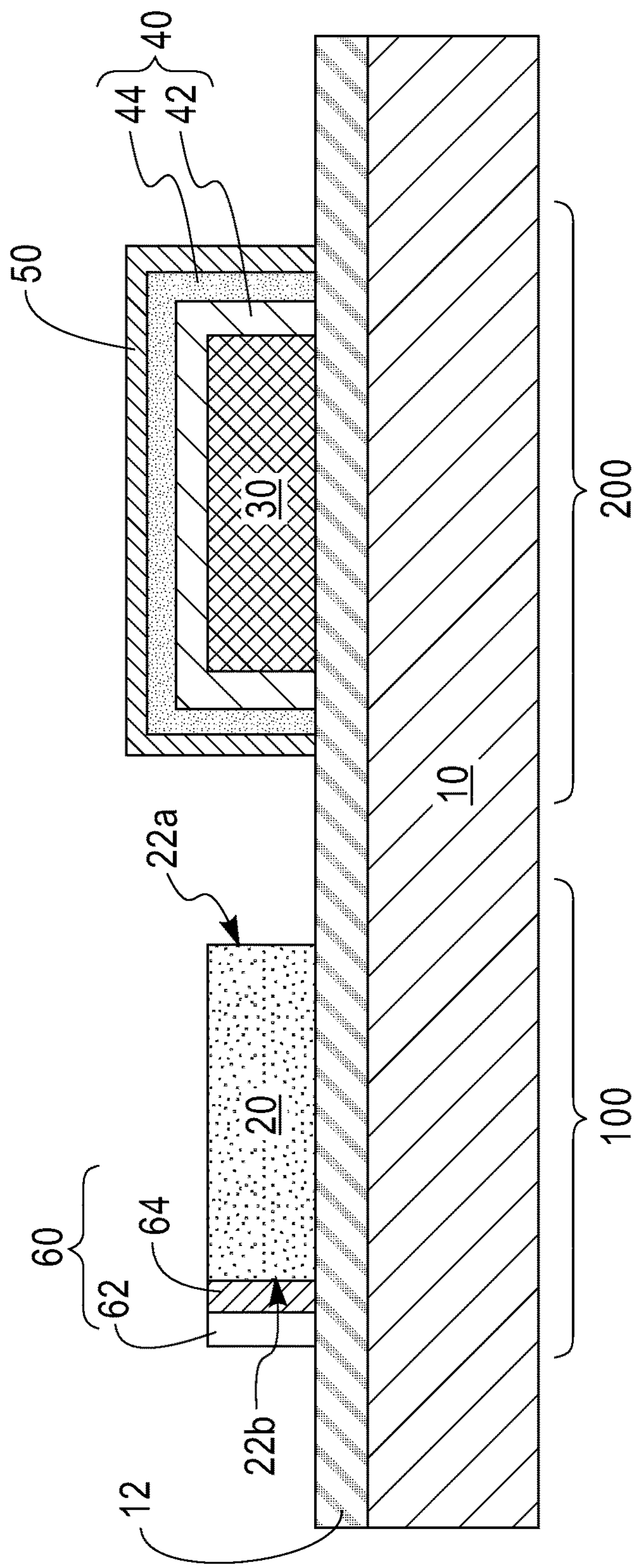

FIG. 10

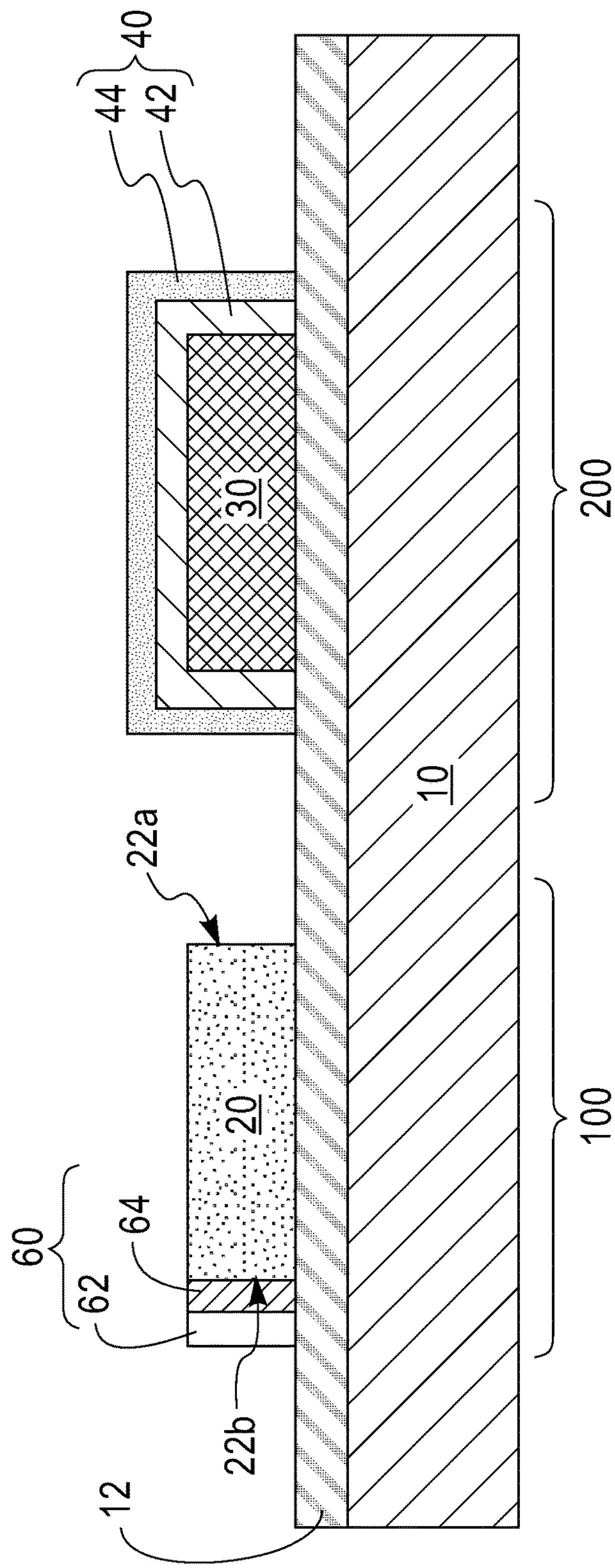

FIG. 11

WAFER SCALE MONOLITHIC INTEGRATION OF LASERS, MODULATORS, AND OTHER OPTICAL COMPONENTS USING ALD OPTICAL COATINGS

BACKGROUND

The present application relates to semiconductor technology, and more particularly to forming optical coatings on optical components that are monolithically integrated on a single semiconductor substrate in a wafer scale process.

High-speed, low-chirp, low power consumption semiconductor lasers and modulators are important components for the next generation of optical networks. Monolithic integration of modulators with lasers on a single integrated chip has been shown to increase the modulation speed and reduce the laser chirp and noise. Different types of optical coating are needed to reduce the optical loss of optical components in the monolithically integrated device. For example, the modulator typically requires an anti-reflection coating so that light emitted from the laser can be coupled effectively into the modulator, while the laser typically requires a high reflection coating on the laser non-output facet so that light incident on the non-output facet can be reflected back into the laser. In the prior art, the fabrication of different types of optical coatings on optical components are for a single row of devices, and thus are not compatible with the monolithic integration scheme in a wafer scale process. As such, there remains a need for a method that allows selectively depositing different types of optical coatings on monolithically integrated optical components in a wafer scale process.

SUMMARY

The present application provides a method that allows selectively depositing different types of optical coatings on monolithically integrated optical components in a wafer scale process. After forming a monolithically integrated device including a laser and a modulator on a semiconductor substrate, an anti-reflection coating layer is formed over the monolithically integrated device and the semiconductor substrate by an atomic layer deposition (ALD) process. The anti-reflection coating layer is lithographically patterned so that an anti-reflection coating is only present on exposed surfaces of the modulator. After forming an etch stop layer portion to protect the anti-reflection coating, a high reflection coating layer is formed over the etch stop layer, the laser and the semiconductor structure by ALD and lithographically patterned to provide a high reflection coating that is formed solely on a non-output facet of the laser.

In one aspect of the present application, a semiconductor structure is provided. The semiconductor structure includes a laser located in a first region of a semiconductor substrate. The laser has a first facet on a first end of the laser through which a laser beam is emitted and a second facet on a second end of the laser opposite the first end. The semiconductor structure further includes a modulator located in a second region of the semiconductor substrate and optically coupled to the laser, an anti-reflection coating present on exposed surfaces of the modulator, and a high reflection coating present on the second facet of the laser.

In another aspect of the present application, a method of forming a semiconductor structure is provided. The method includes first providing a laser in a first region of a semiconductor substrate and a modulator in a second region of the semiconductor substrate and optically coupled to the laser. The laser has a first facet on a first end of the laser through which a laser beam is emitted and a second facet on a second end of the laser opposite the first end. An anti-reflection coating is then formed on exposed surfaces of the modulator. Next, a high reflection coating is formed on the second facet of the laser.

BRIEF DESCRIPTION OF SEVERAL VIEWS OF THE DRAWINGS

FIG. **1** is a cross-sectional view of an exemplary semiconductor structure including a laser located on a first portion of a semiconductor substrate in accordance with an embodiment of the present application.

FIG. **2** illustrates components of the laser of FIG. **1** in accordance with an embodiment of the present application.

FIG. **3** is a cross-sectional view of the exemplary semiconductor structure of FIG. **1** after forming a modulator in a second region of the semiconductor substrate.

FIG. **4** illustrates components of the modular of FIG. **3** in accordance with an embodiment of the present application.

FIG. **5** is a cross-sectional view of the exemplary semiconductor structure of FIG. **3** after forming an anti-reflection coating layer over the laser, the modulator and the semiconductor substrate.

FIG. **6** is a cross-sectional view of the exemplary semiconductor structure of FIG. **5** after forming an anti-reflection coating over exposed surfaces of the modulator.

FIG. **7** is a cross-sectional view of the exemplary semiconductor structure of FIG. **6** after forming an etch stop layer over the anti-reflection coating, the laser and the semiconductor substrate.

FIG. **8** is a cross-sectional view of the exemplary semiconductor structure of FIG. **7** after forming an etch stop layer portion over the anti-reflection coating.

FIG. **9** is a cross-sectional view of the exemplary semiconductor structure of FIG. **8** after forming a high reflection coating layer over the laser, the etch stop layer portion and the semiconductor substrate.

FIG. **10** is a cross-sectional view of the exemplary semiconductor structure of FIG. **9** after forming a high reflection coating over a non-output facet of the laser.

FIG. **11** is a cross-sectional view of the exemplary semiconductor structure of FIG. **10** after removing the etch stop layer portion from the anti-reflection coating.

DETAILED DESCRIPTION

The present application will now be described in greater detail by referring to the following discussion and drawings that accompany the present application. It is noted that the drawings of the present application are provided for illustrative purposes only and, as such, the drawings are not drawn to scale. It is also noted that like and corresponding elements are referred to by like reference numerals.

In the following description, numerous specific details are set forth, such as particular structures, components, materials, dimensions, processing steps and techniques, in order to provide an understanding of the various embodiments of the present application. However, it will be appreciated by one of ordinary skill in the art that the various embodiments of the present application may be practiced without these specific details. In other instances, well-known structures or processing steps have not been described in detail in order to avoid obscuring the present application.

Referring now to FIG. **1**, there is illustrated an exemplary semiconductor structure including a laser **20** located in a first region **100** of a semiconductor substrate **10**.

The semiconductor substrate **10** may include any semiconductor material such as, for example, silicon (Si), germanium (Ge), a silicon germanium (SiGe) alloy, SiGeC, SiC, an III-V compound semiconductor or an II-VI compound semiconductor. Multilayers of these semiconductor materials can also be used as the semiconductor material of semiconductor substrate **10**. The thickness of the semiconductor substrate **10** can be from 50 μm to 2 mm, although lesser and greater thicknesses can also be employed.

The semiconductor substrate **10** may have any crystal orientation including, for example, {100}, {110} or {111}. In some embodiments, the semiconductor substrate **10** may be a single crystalline semiconductor material. Typically, and in one embodiment of the present application, the semiconductor substrate **10** is single crystal silicon. In other embodiments, the semiconductor substrate **10** is a polycrystalline semiconductor material such as, for example, polycrystalline silicon.

In one embodiment and when the semiconductor substrate **10** is composed of silicon, a semiconductor seed layer **12** may be formed on top of the semiconductor substrate **10**. The semiconductor seed layer **12** may include Ge or SiGe and may be deposited utilizing an epitaxial growth (or deposition) process including molecular beam epitaxy (MBE) or metal-organic chemical vapor deposition (MOCVD) so that the semiconductor seed layer **12** is epitaxially aligned with the semiconductor substrate **10**. By "epitaxially aligned" it is meant that the semiconductor seed layer **12** has a same crystal orientation as that of the semiconductor substrate **10**. The thickness of the semiconductor seed layer **12** that is formed can be from 10 nm to 100 nm, although lesser and greater thicknesses can also be employed.

The laser **20** has an output facet **22***a* located at a first end of the laser **20** through which the laser beam is emitted and a non-output facet **22***b* located at a second end of the laser **20** opposite the first end. In one embodiment and as shown in FIG. **2**, the laser **20** may include, for bottom to top, a first bottom cladding layer **24**, a first active layer **26** and a first top cladding layer **28**. The first active layer **26** is layer within which light is emitted by recombination of carriers. The first bottom cladding layer **24** and the from top cladding layer **28** are layers for increasing a carrier density in the first active layer **26**.

The first bottom cladding layer **24** may include an III-V compound semiconductor material. In one embodiment, the first bottom cladding layer **24** comprises AlGaAs. The semiconductor material that provides the first bottom cladding layer **24** may be of a first conductivity type (p-type or n-type). The p-type dopants comprise a group II element such as Mg, Zn, Ca, Sr, or Ba. The n-type dopants comprise a group IV element such as Si, Ge, Sn, Se, or Te. The first bottom cladding layer **24** may be formed utilizing an epitaxially growth process such as, for example, MBE or MOCVD. The first bottom cladding layer **24** that is formed is epitaxially aligned with the semiconductor seed layer **12**.

The first active layer **26** may include an III-V compound semiconductor material. In one embodiment, the first active layer **26** comprises GaAs. Alternatively, the first active layer **26** may be formed with a single quantum well structure or a multi quantum well structure. In one embodiment, the first active layer **26** comprises a quantum well layer formed of $In_xGa_{1-x}N$ and a quantum barrier layer formed of GaN alternately. Here, x is adjusted through $0 \leq x \leq 1$. The first active layer **26** can be formed utilizing an epitaxial growth process such as, for example, MBE or MOCVD. The first active layer **26** that is formed is epitaxially aligned with the first bottom cladding layer **24**.

The first top cladding layer **28** may include an III-V compound semiconductor material that is the same as, or different from, the first bottom cladding layer **24**. In one embodiment, the first top cladding layer **28** comprises AlGaAs. The semiconductor material that provides the first top cladding layer **28** may be of a second conductivity type opposite the first conductivity type. The first top cladding layer **28** can be formed utilizing an epitaxial growth process such as, for example, MBE or MOCVD. The first top cladding layer **28** that is formed is epitaxially aligned with the first active layer **26**.

The laser **20** can be formed by first forming a material stack of the first bottom cladding layer **24**, the first active layer **26** and the first top cladding layer **28** over the semiconductor substrate **10** or the semiconductor seed layer **12**, if present, and lithographically patterning the material stack (**24**, **26**, **28**). The lithographic patterning of the material stack (**24**, **26**, **28**) can be performed by a dry etch, such as, for example, reactive ion etching (RIE) to define the output facet **22***a* and the non-output facet **22***b* of the laser **20**. The laser **20** that is formed may have a length, L**1**, of about 500 μm and a height, h**1**, of about 3 μm.

Referring to FIG. **3**, there is illustrated the exemplary semiconductor structure of FIG. **1** after forming a modulator **30** in a second region **200** of the semiconductor substrate **10**. A monolithically integrated device including the laser **20** and the modulator **30** is thus formed. The modulator **30** may have a length, L**2**, of about 500 μm and a height, h**2**, of about 3 μm. The distance, d, between the laser **20** and the modulator **30** is less than 1 μm to ensure that the light emitted from the laser **20** can be coupled into the modular **30**.

In one embodiment and as shown in FIG. **4**, the modulator **30** may include, from bottom to top, a second bottom cladding layer **32**, a second active layer **34** and a second top cladding layer **36**. The second bottom cladding layer **32** and the second top cladding layer **36** are formed of a III-V compound semiconductor material, respectively. The second bottom cladding layer **32** has, for example, the first conductivity type (for example, n-type). The second top cladding layer **36** has a second conductivity type (for example, p-type) opposite the first conductivity type. In one embodiment, the second bottom cladding layer **32** is composed of an n-type InP, while the second top cladding layer **36** is composed of a p-type InP. The second active layer **34** may have a quantum well structure comprising InGaAsP layers (not shown) separated by at least one InP barrier layer (not shown).

The modulator **30** can be formed by first applying a dielectric oxide layer (not shown) over the semiconductor substrate **10** or the semiconductor seed layer **12**, if present, and etching the dielectric oxide layer to expose the second region **200** of the semiconductor substrate **10** by an anisotropic etch. The anisotropic etch can be a dry etch such as, for example, reactive ion etching or a wet chemical etch. After etching the dielectric oxide layer, the laser **20** in the first region **100** remains covered by the dielectric oxide layer. Subsequently, the second bottom cladding layer **32**, the second active layer **34** and the second top cladding layer **36** that constitute the modulator **30** are epitaxially grown on the exposed surface of the semiconductor substrate **10** or the semiconductor seed layer **12**, if present, sequentially.

In another embodiment, the laser **20** and the modular **30** can be monolithically integrated by a wafer bonding process known in the art.

In the present application, although two types of optical components, i.e., laser **20** and modulator **30**, are described and illustrated, other types of optical components (e.g., photodetector, waveguide) can also be formed on the semiconductor substrate **10** and integrated with the laser **20** and/or the modulator **30** of the present application.

Referring to FIG. **5**, there is illustrated the exemplary semiconductor structure of FIG. **3** after forming an anti-reflection coating layer **40**L over the laser **20**, the modulator **30** and exposed surface of the semiconductor substrate **10** or the semiconductor seed layer **12**, if present. The anti-reflection coating layer **40**L may include a stack of alternating layers of different refractive indices. In one embodiment and as shown in FIG. **5**, the anti-reflection coating layer **40**L includes a first coating layer **42**L having a high refractive index and a second coating layer **44**L having a low refractive index overlying the first dielectric layer **42**L. For example, the first coating layer **42**L may have a refractive index of at least 1.85 and can be formed of silicon nitride (SiN), hafnium oxide (HfO_2), titanium nitride (TiN), tantalum oxide (Ta_2O_5) or titanium oxide (TiO_2). The second coating layer **44**L may have a refractive index of less than 1.8 and can be formed of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), or silicon oxynitride (SiON). In one embodiment, the anti-reflection coating layer **40**L is composed of a SiN first coating layer **42**L and a SiO_2 second coating layer **44**L. Although the anti-reflection coating layer **40**L illustrated in FIG. **5** is formed of a pair of coating layers **42**L, **44**L, the number of pairs of the coating layers **42**L, **44**L is not limited thereto. More layers of the first coating layer **42**L and the second coating layer **44**L can be alternately superposed so far as a necessary transmittance is obtained in the anti-reflection coating layer **40**L.

The first coating layer **42**L and the second coating layer **44**L of the anti-reflection coating layer **40**L may be formed by atomic layer deposition (ALD). The ALD process allows a very accurate control of film thickness and film quality. The first coating layer **42**L that is formed may have a thickness from 15 nm to 50 nm, although lesser and greater thicknesses can also be employed. The second coating layer **44**L that is formed may have a thickness from 160 nm to 200 nm, although lesser and greater thicknesses can also be employed.

Referring to FIG. **6**, there is illustrated the exemplary semiconductor structure of FIG. **5** after forming an anti-reflection coating **40** over exposed surfaces of the modulator **30**. A first mask layer (not shown) is first applied over the anti-reflection coating layer **40**L. The first mask layer can be a photoresist layer or a photoresist layer in conjunction with hardmask layer(s). The first mask layer is then lithographically patterned to form openings therein. The openings expose portions of the anti-reflection coating layer **40**L that are not present on the exposed surfaces of the modulator **30**. A remaining portion of the mask layer constitutes a patterned first mask layer.

Subsequently, portions of the anti-reflection coating layer **40**L that are not covered by the patterned first mask layer are removed. An anisotropic etch, which can be a dry etch such as RIE or a wet chemical etch may be performed to remove the materials of first coating layer **42**L and the second coating layer **44**L in the anti-reflection coating layer **40**L selective to materials of the lasers **20** and the semiconductor substrate **10** or the semiconductor seed layer **12**, if present. The portion of the anti-reflection coating layer **40**L that remains on the modulator **30** constitutes the anti-reflection coating **40**. The anti-reflection coating **40** comprises a first coating **42** which is a remaining portion of the first coating layer **42**L and a second coating **44** which is a remaining portion of the second coating layer **44**L. The anti-reflection coating **40** that is formed on the exposed surfaces (i.e., a top surface and input and output surfaces) of the modulator **30** can effectively decreases light reflection and hence improving transmission of the modulator **30**. Upon formation of the anti-reflection coating **40**, the patterned first mask layer can be removed, for example, by oxygen-based plasma etching.

Referring to FIG. **7**, there is illustrated the exemplary semiconductor structure of FIG. **6** after forming an etch stop layer **50**L over the anti-reflection coating **40**, the laser **20** and the semiconductor substrate **10** or the semiconductor seed layer **12**, if present. The etch stop layer **50**L may include a semiconductor material such as, for example, amorphous silicon, or a metal such as, for example, copper (Cu) or titanium nitride (TiN). The etch stop layer **50**L may be depositing using a conventional deposition process such as, for example, chemical vapor deposition (CVD), physical vapor deposition (PVD), plasma enhanced chemical vapor deposition (PECVD) or ALD. The etch stop layer **50**L that is formed may have a thickness from 10 nm to 50 nm, although lesser and greater thickness can also be employed.

Referring to FIG. **8**, there is illustrated the exemplary semiconductor structure of FIG. **6** after removing portions of the etch stop layer **50**L that are not present on the anti-reflection coating **40** to provide an etch stop layer portion **50**. The etch stop layer portion **50** protects the underlying anti-reflection coating **40** during the subsequent processing steps. A second mask layer (not shown) is first applied over the etch stop layer **50**L. The second mask layer can be a photoresist layer or a photoresist layer in conjunction with hardmask layer(s). The second mask layer is then lithographically patterned to form openings therein. The openings expose portions of the etch stop layer **50**L that are not present on the anti-reflection coating **40**. A remaining portion of the mask layer constitutes a patterned second mask layer.

Subsequently, portions of the etch stop layer **50**L that are not covered by the patterned second mask layer are removed. An anisotropic etch, which can be a dry etch such as RIE or a wet chemical etch, may be performed to remove the material of etch stop layer **50**L selective to materials of the lasers **20** and the semiconductor substrate **10** or the semiconductor seed layer **12**, if present. The portion of the etch stop layer **50**L that remains on the anti-reflection coating **40** constitutes the etch stop layer portion **50**. Upon formation of the etch stop layer portion **50**, the patterned second mask layer can be removed, for example, by oxygen-based plasma etching.

Referring to FIG. **9**, there is illustrated the exemplary semiconductor structure of FIG. **8** after forming a high reflection coating layer **60**L over the laser **20**, the etch stop layer portion **50** and exposed surface of the semiconductor substrate **10** or the semiconductor seed layer **12**, if present. The high reflection coating layer **60**L typically has a reflectance of not less than 70%, more preferably not less than 90%. The high reflection coating layer **60**L may include a stack of alternating layers of different refractive indices. In one embodiment and as shown in FIG. **9**, the high reflection coating layer **60**L includes a third coating layer **62**L having a low refractive index and a fourth coating layer **64**L having a high refractive index. Exemplary low refractive index materials include, but are not limited to SiO_2, Al_2O_3 or SiON. Exemplary high refractive index materials include, but are not limited to SiN, HfO_2, TiN, Ta_2O_5 or TiO_2. For example, the third coating layer **62**L may include SiO_2, while the fourth coating layer **64**L may include Ta_2O_5.

Although the high reflection coating layer **60**L illustrated in FIG. **9** is formed of a pair of coating layers **62**L, **64**L, the number of pairs of the coating layers **62**L, **64**L is not limited thereto. More layers of the third coating layer **62**L and the fourth coating layer **64**L can be alternately superposed so far as a necessary reflectance is obtained in the high reflection coating layer **60**L.

The respective coating layers (i.e., the third coating layer **62**L and the fourth coating layer **64**L may be formed by ALD. The thickness (t) of each of the third coating layer **62**L and the fourth coating layer **64**L is set to satisfy the following equation: $t<\lambda/4n$, wherein λ is an oscillation wavelength of a laser beam; n is refractive index of a coating layer.

Referring to FIG. **10**, there is illustrated the exemplary semiconductor structure of FIG. **9** after forming a high reflection coating **60** over the non-output facet **22***b* of the laser **20**. A third mask layer (not shown) is first applied over the high reflection coating layer **60**L. The third mask layer can be a photoresist layer or a photoresist layer in conjunction with hardmask layer(s). The third mask layer is then lithographically patterned to form openings therein. The openings expose portions of the high reflection coating layer **60**L that are not present on the non-output facet **22***b* of the laser **20**. A remaining portion of the third mask layer constitutes a patterned third mask layer.

Subsequently, portions of the high reflection coating layer **60**L that are not covered by the patterned third mask layer are removed. An anisotropic etch, which can be a dry etch such as RIE or a wet chemical etch, may be performed to remove the materials of the third coating layer **62**L and the fourth coating layer **64**L in the high reflection coating layer **60**L selective to materials of the lasers **20**, the etch stop layer portion **50** and the semiconductor substrate **10** or the semiconductor seed layer **12**, if present. The portion of the high reflection coating layer **60**L that remains on the non-output facet **22***b* of the laser **20** constitutes the high reflection coating **60**. In one embodiment, the high reflection coating **60** comprises a third coating **62** which is a remaining portion of the third coating layer **62**L and a fourth coating **64** which is a remaining portion of the fourth coating layer **64**L. Upon formation of the high reflection coating **60**, the patterned third mask layer can be removed, for example, by oxygen-based plasma etching.

The high reflection coating **60** that remains on the non-output facet **22***b* of the laser **20** causes the laser beam that is incident on the non-output facet **22***b* to be reflected back to the laser **20** and ultimately out of the output facet **22***a* of the laser **20**, thus effectively suppressing the optical loss due to the light absorption by the non-output facet **22***b* of the laser **20**. As a result, the stability and efficiency of the laser **20** can be improved.

Referring to FIG. **11**, there is illustrated the exemplary semiconductor structure of FIG. **10** after removing the etch stop layer portion **50** from the anti-reflection coating **40**. The etch stop layer portion **50** may be removed selective to the anti-reflection coating **40**, the laser **20**, the high reflection coating **60** and the semiconductor substrate **10** or the semiconductor seed layer **12**, if present. In one embodiment, the etch stop layer portion **50** may be removed by a dry etch, such as RIE or a wet chemical etch.

In the present application, when the monolithically integrated device also includes other types of optical components, the same ALD and lithographic patterning processes as described above can be applied to form desirable optical coatings on the other types of optical components.

In the present application, by repeating the processes of depositing a respective coating layer over optical components that are present on a semiconductor substrate and lithographic patterning the coating layer, different types of optical coatings (e.g., anti-reflection coating and high-reflection coating) can be formed selectively on different types of optical components depending on the need. The wafer scale integration of optical components is thus achieved in a cost effective way.

While the present application has been particularly shown and described with respect to preferred embodiments thereof, it will be understood by those skilled in the art that the foregoing and other changes in forms and details may be made without departing from the spirit and scope of the present application. It is therefore intended that the present application not be limited to the exact forms and details described and illustrated, but fall within the scope of the appended claims.

What is claimed is:

1. A method of forming a semiconductor structure comprising:

providing a laser in a first region of a semiconductor substrate and a modulator in a second region of the semiconductor substrate that is optically coupled to the laser, wherein the laser has a first facet on a first end of the laser that is proximal to the modulator and a second facet on a second end of the laser opposite the first end;

forming an anti-reflection coating on exposed surfaces of the modulator;

forming an etch stop layer portion over the anti-reflection coating; and

forming a high reflection coating on the second facet of the laser, wherein the forming the high reflection coating on the second facet of the laser comprises:

forming a high reflection coating layer on the etch stop layer portion, the laser and the semiconductor substrate, wherein the high reflection coating layer comprises at least a pair of a third coating layer and a fourth coating layer having different refractive indices, wherein the third coating layer contacts the exposed surfaces of the modulator

forming a third mask layer over the high reflection coating layer,

patterning the third mask layer to expose portions of the high reflection coating layer that are not present on the second facet of the laser,

removing the exposed portions of the high reflection coating layer to provide the high reflection coating, and

removing a remaining portion of the third mask layer.

2. The method of claim **1**, wherein the forming the anti-reflection coating on the exposed surfaces of the modulator comprises:

forming an anti-reflection coating layer over the modulator, the laser and the semiconductor substrate;

forming a first mask layer over the anti-reflection coating layer;

patterning the first mask layer to expose portions of the anti-reflection coating layer that are not present on the exposed surfaces of the modulator;

removing the exposed portions of the anti-reflection coating layer to provide the anti-reflection coating; and

removing a remaining portion of the first mask layer.

3. The method of claim **2**, wherein the anti-reflection coating layer comprises at least one pair of a first coating layer and a second coating layer having different refractive indices, wherein the first coating layer contacts the exposed surfaces of the modulator.

4. The method of claim 3, wherein the first coating layer has a first refractive index, and the second coating layer has a second refractive index, wherein the first refractive index is greater than the second refractive index.

5. The method of claim 4, wherein the first coating layer comprises silicon nitride (SiN), hafnium oxide (HfO_2), titanium nitride (TiN), tantalum oxide (Ta_2O_5) or titanium oxide (TiO_2), and the second coating layer comprises silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) or silicon oxynitride (SiON).

6. The method of claim 2, wherein the anti-reflection coating layer is formed by atomic layer deposition.

7. The method of claim 2, wherein the exposed portions of the anti-reflection coating layer is removed by reactive ion etching.

8. The method of claim 1, wherein the anti-reflection coating is in direct contact with sidewalls and a top surface of the modulator.

9. The method of claim 1, wherein the etch stop layer comprises amorphous silicon, copper or titanium nitride.

10. The method of claim 1, wherein the forming the etch stop layer portion comprises:
- forming an etch stop layer over the anti-reflection coating, the laser and the semiconductor substrate;
- forming a second mask layer over the etch stop layer;
- patterning the second mask layer to expose portions of the etch stop layer that are not present on the anti-reflection coating;
- removing the exposed portions of the etch stop layer to provide the etch stop layer portion; and
- removing a remaining portion of the second mask layer.

11. The method of claim 1, wherein the third coating layer has a third refractive index, and the fourth coating layer has a fourth refractive index, wherein the third refractive index is less than the fourth refractive index.

12. The method of claim 11, wherein the third coating layer comprises SiO_2, Al_2O_3 or SiON, and the fourth coating layer comprises SiN, HfO_2, TiN, Ta_2O_5 or TiO_2.

13. The method of claim 1, further comprising removing the etch stop layer portion from the anti-reflection coating after the forming the high reflection coating on the second facet of the laser.

14. The method of claim 1, further comprising forming the laser in the first region of the semiconductor substrate, wherein the forming the laser comprises:
- forming a material stack including, from bottom to top, a first bottom cladding layer, a first active layer and a first top cladding layer over an entire top surface of the semiconductor substrate, wherein the first bottom cladding layer, the first active layer and the first top cladding layer are epitaxially aligned with the semiconductor substrate; and
- lithographically patterning the material stack by reactive ion etching to form the laser in the first region of the semiconductor substrate.

15. The method of claim 1, further comprising forming the modulator in the second region of the semiconductor substrate, wherein the forming the modulator comprises:
- forming a dielectric oxide layer over the semiconductor substrate and the laser;
- patterning the dielectric oxide layer by an anisotropic etch to expose the second region of the semiconductor substrate, wherein the laser in the first region of the semiconductor substrate remains covered by the dielectric oxide layer; and
- forming the modulator comprising, from bottom to top, a second bottom cladding layer, a second active layer and a second top cladding layer on the second region of the semiconductor substrate, wherein the second bottom cladding layer, the second active layer and the second top cladding layer are epitaxially aligned with the semiconductor substrate.

16. The method of claim 1, further comprising forming a semiconductor seed layer on a top surface of the semiconductor substrate, wherein the semiconductor layer is epitaxially aligned with the semiconductor substrate, and the laser and the modulator are located on a top surface of the semiconductor seed layer.

17. The method of claim 16, wherein the semiconductor seed layer comprises Ge or SiGe.

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