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**Kuo et al.**

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(54) **OPTICAL SYSTEM**

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**Related U.S. Application Data**

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**G02B 6/30** (2006.01)

(52) **U.S. Cl.**  
CPC ..... **G02B 6/305** (2013.01)

(58) **Field of Classification Search**  
CPC ..... G02B 6/1228; G02B 6/124; G02B 6/125;  
G02B 6/13; G02B 6/136; G02B 6/138;  
G02B 6/14; G02B 6/305

See application file for complete search history.

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*Primary Examiner* — Michael P Mooney

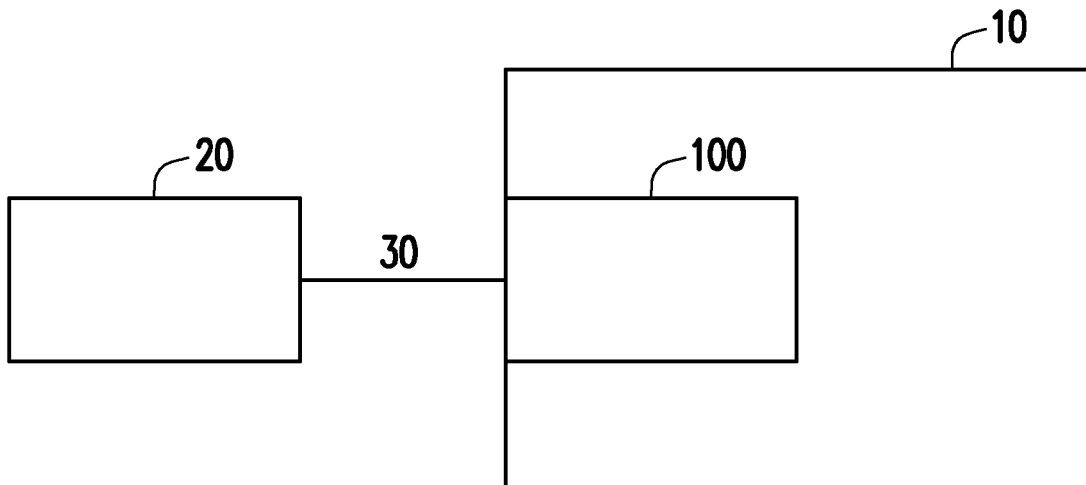
(74) *Attorney, Agent, or Firm* — JCIPRNET

(57) **ABSTRACT**

An optical coupler is provided. The optical coupler includes: a first optical structure, and a second optical structure disposed over the first optical structure. The first optical structure includes: a first substrate, a first cladding layer disposed on the first substrate, and a first waveguide disposed on the first cladding layer. The first waveguide includes a first coupling portion, and the first coupling portion including a first taper part. The second optical structure includes: a second substrate, a dielectric layer disposed on the second substrate; and a second waveguide disposed on the dielectric layer. The second waveguide includes a second coupling portion, and the second coupling portion including a second taper part. The second taper part is disposed on and optically coupled with the first taper part, and a taper direction of the first taper part is the same as a taper direction of the second taper part.

**20 Claims, 20 Drawing Sheets**

**1**



1

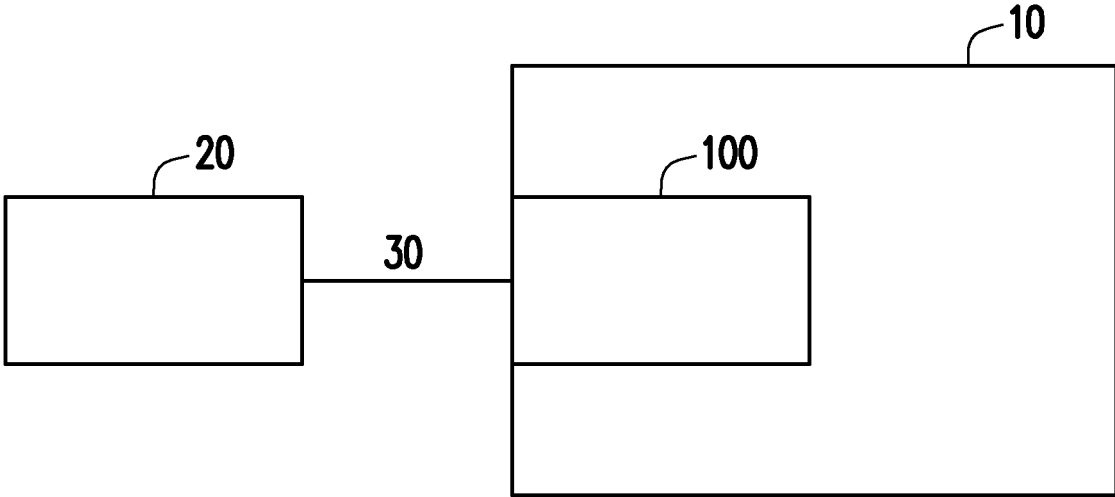
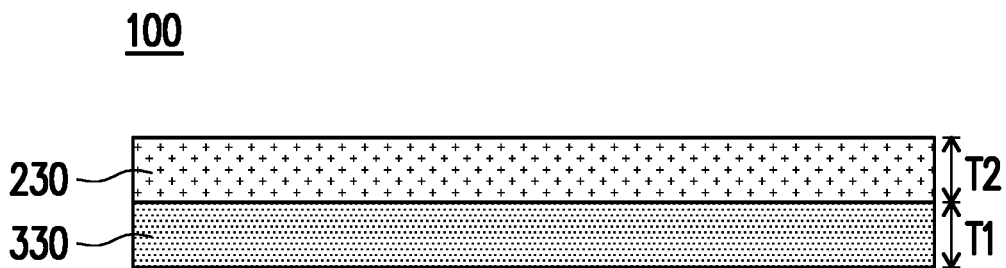
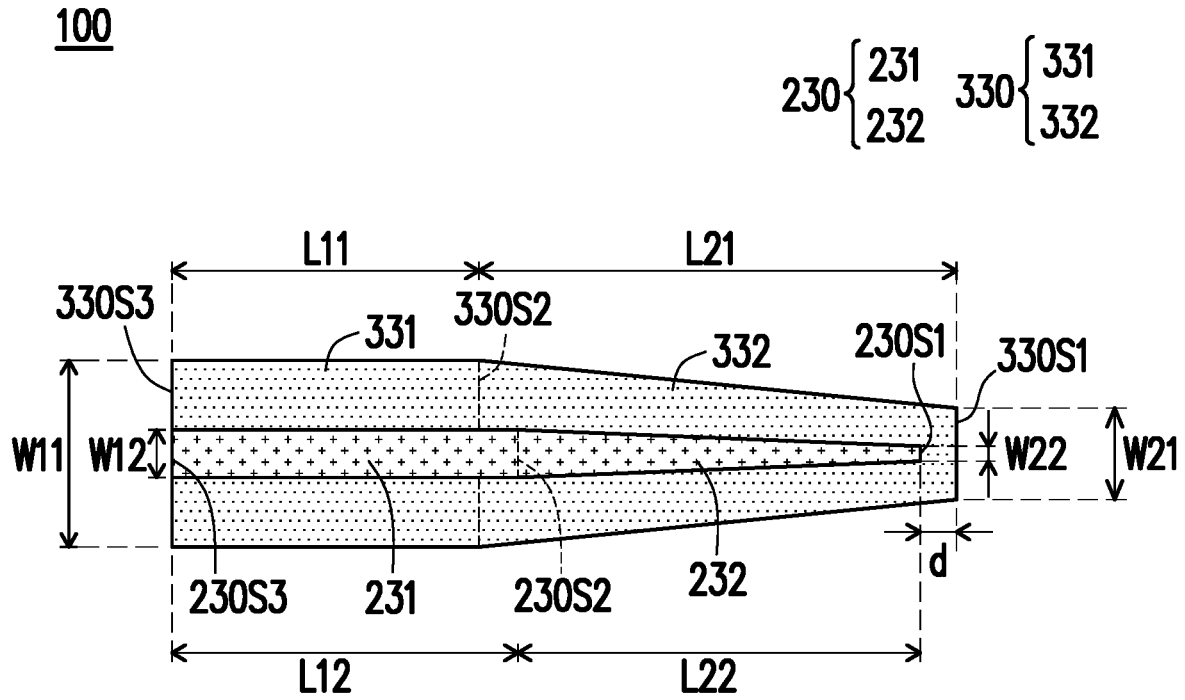


FIG. 1



200

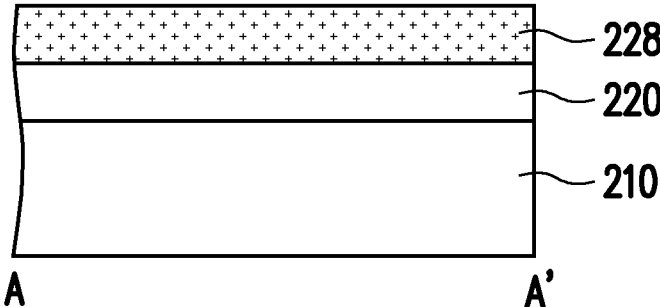


FIG. 3A

200

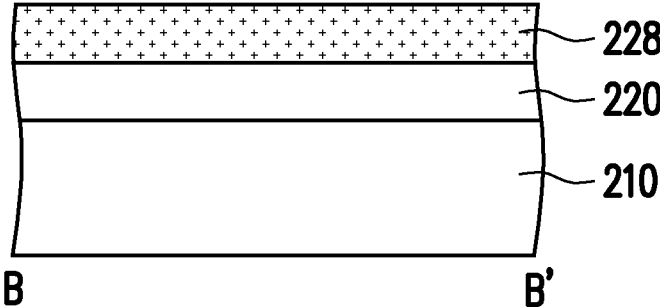


FIG. 3B

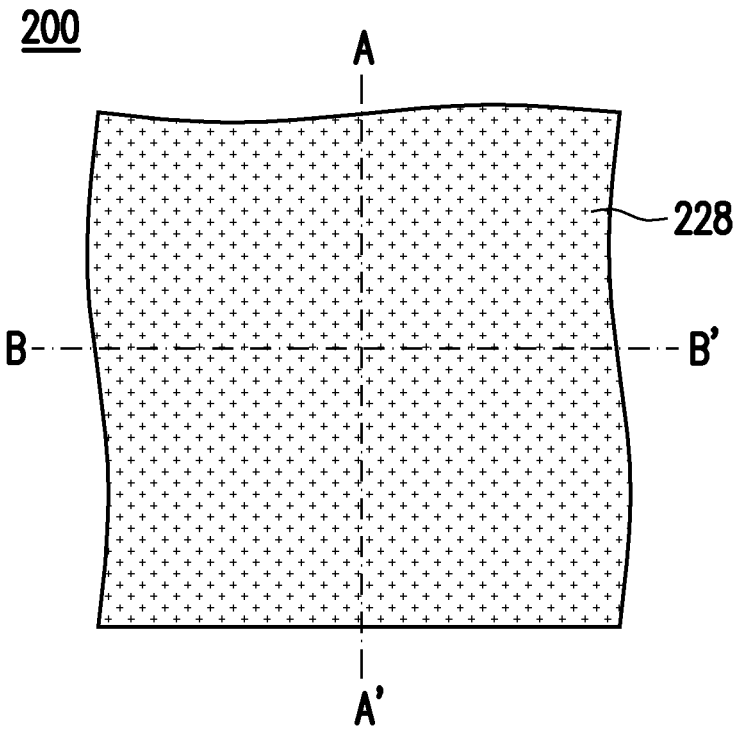


FIG. 3C

200

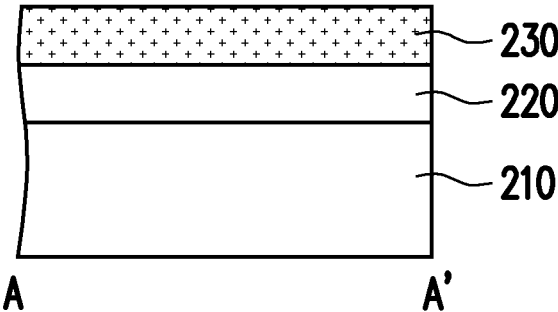


FIG. 4A

200

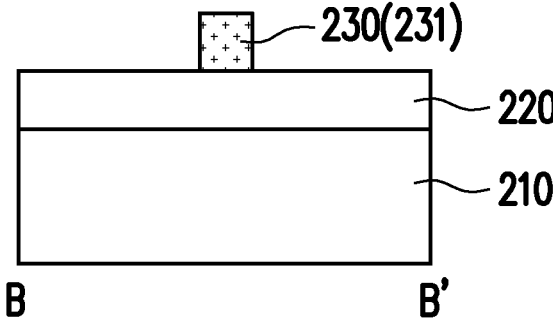


FIG. 4B

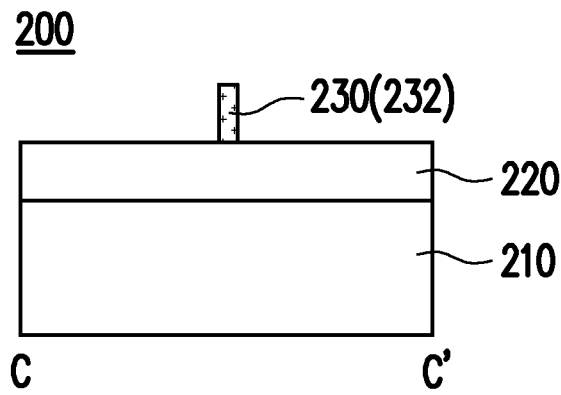


FIG. 4C

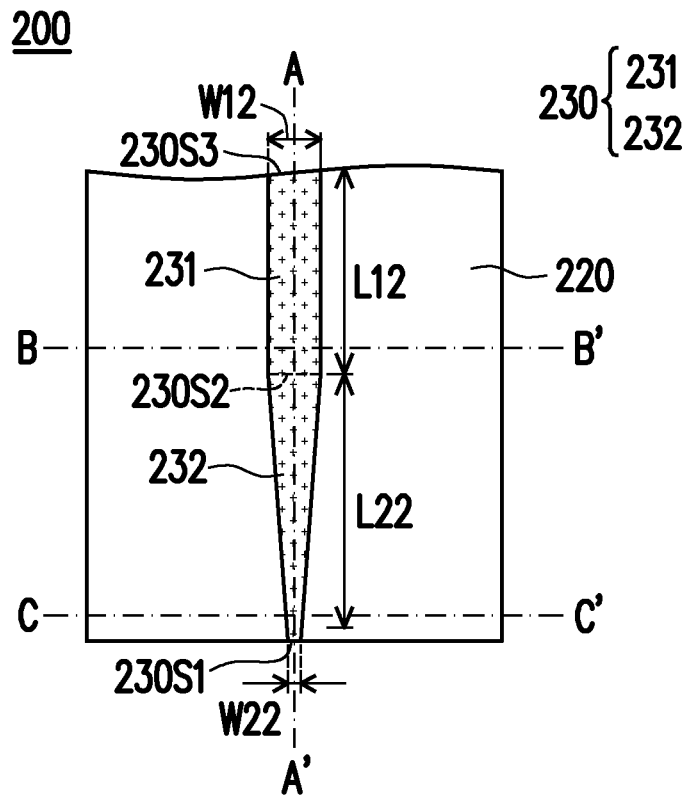


FIG. 4D

300

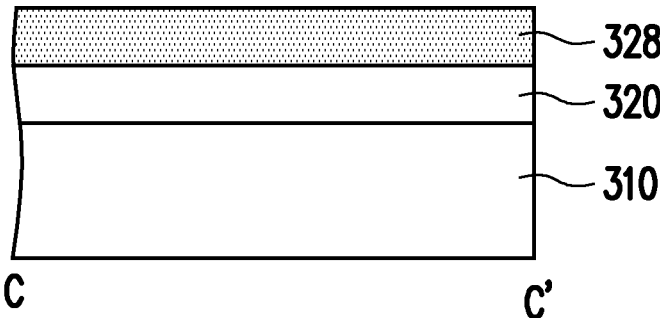


FIG. 5A

300

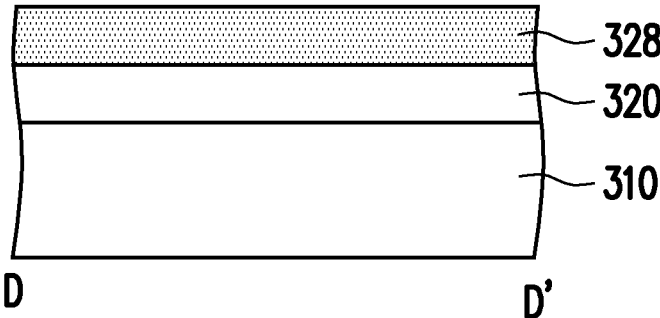


FIG. 5B



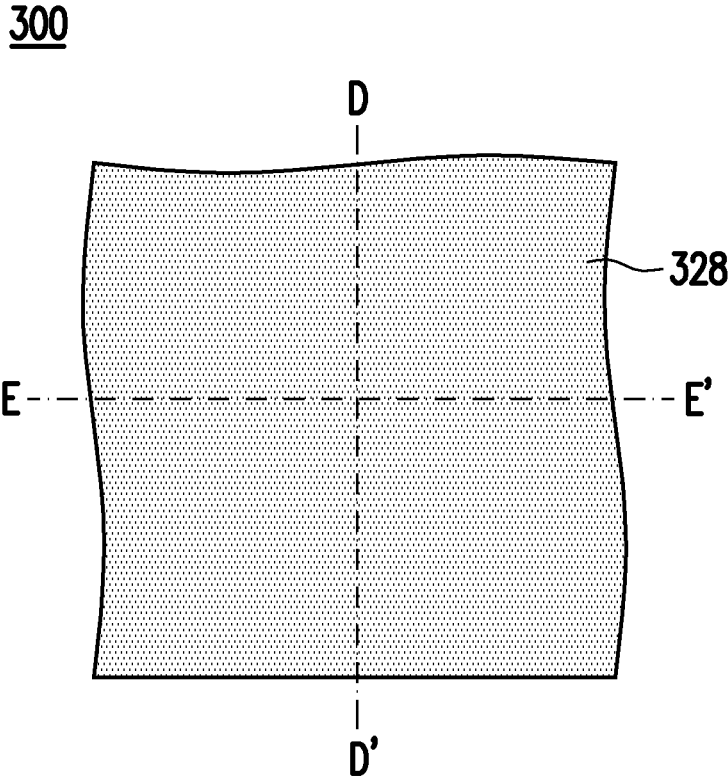


FIG. 5C

300

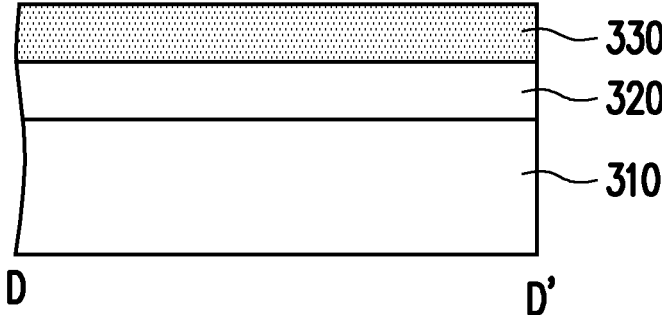


FIG. 6A

300

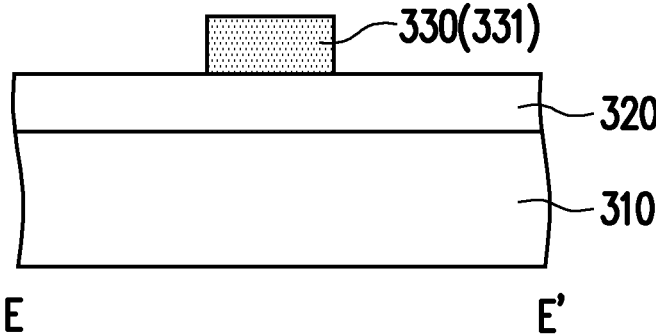


FIG. 6B

300

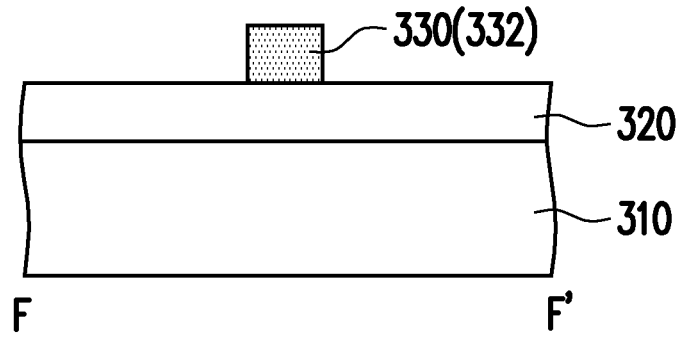


FIG. 6C

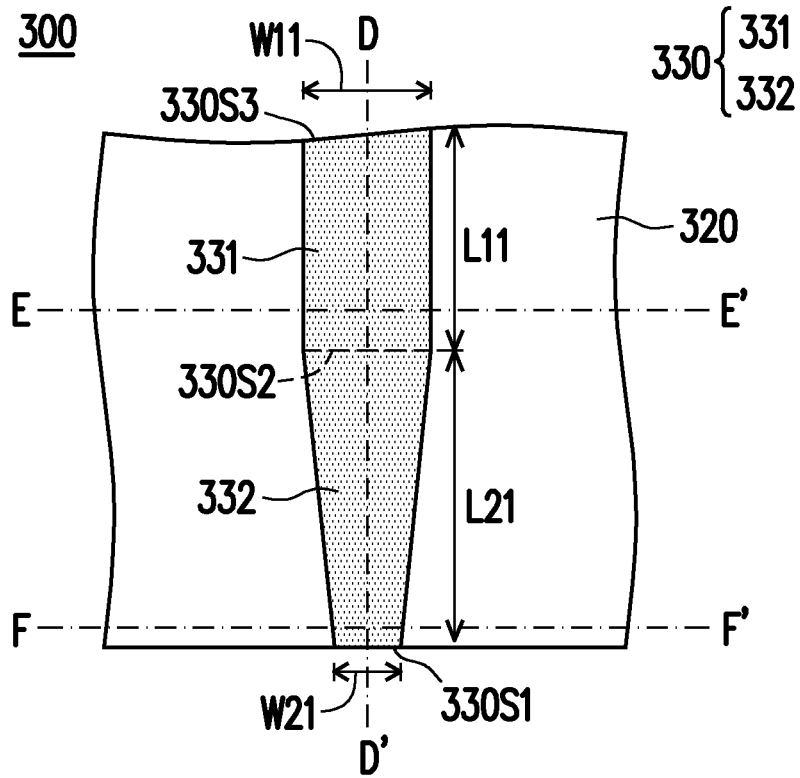


FIG. 6D

300

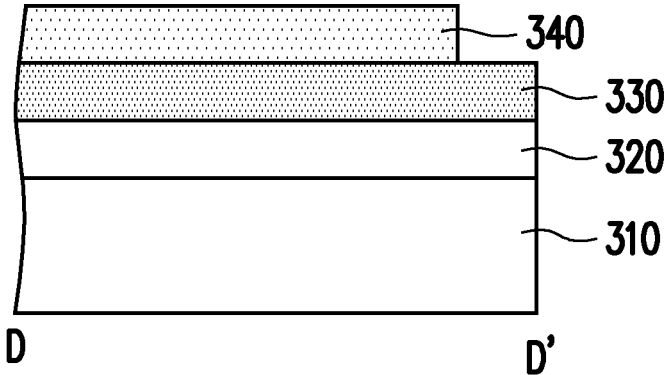


FIG. 7A

300

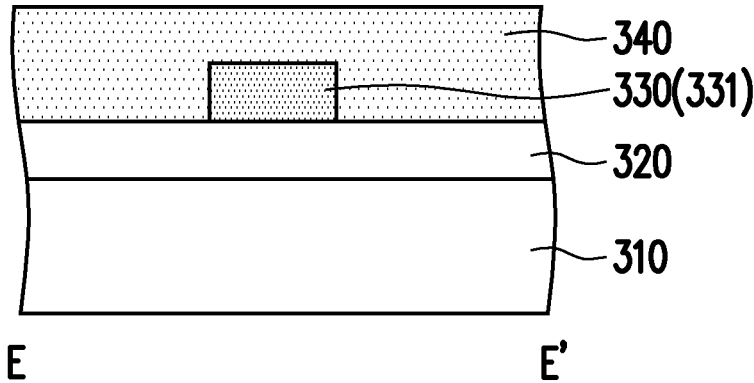


FIG. 7B

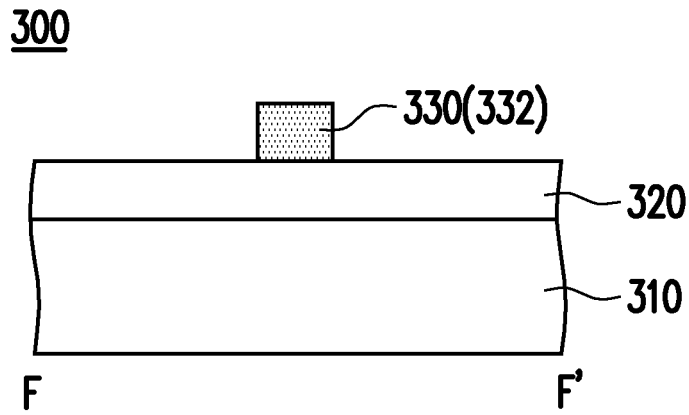


FIG. 7C

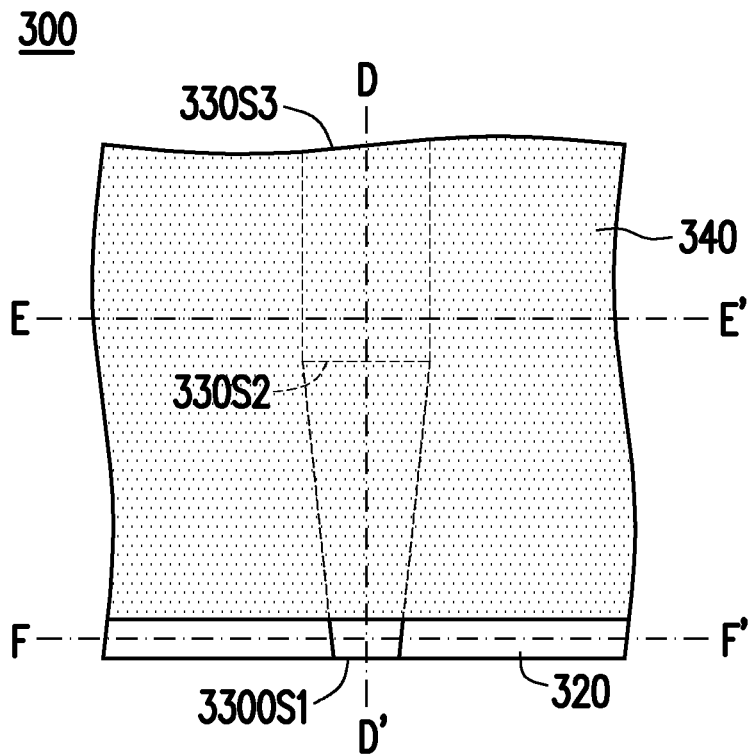


FIG. 7D

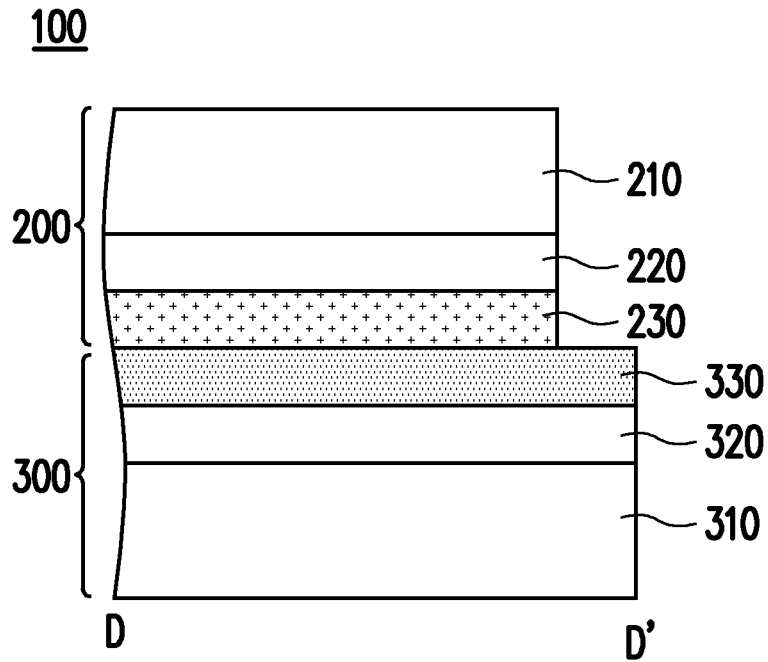


FIG. 8A

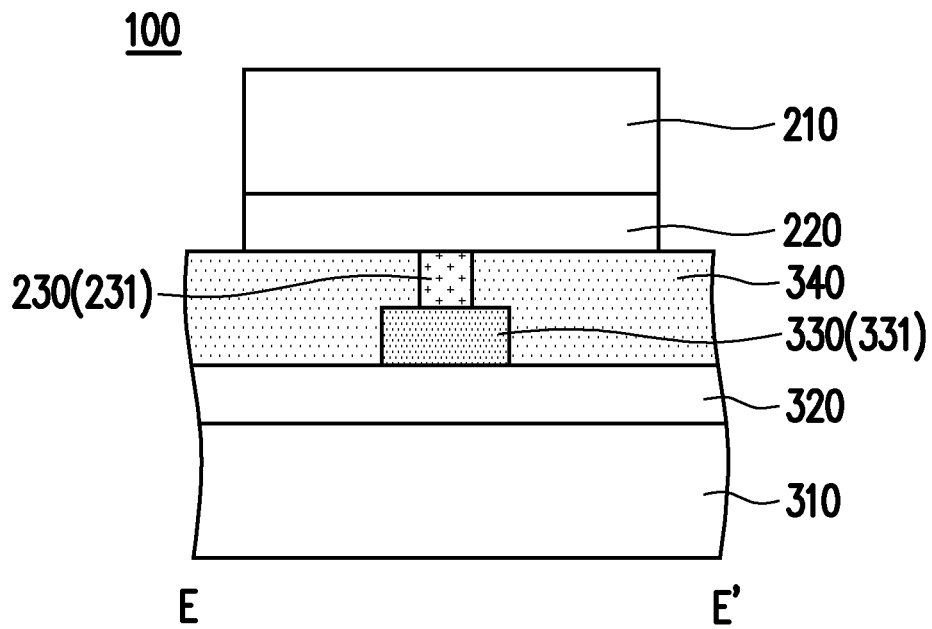


FIG. 8B

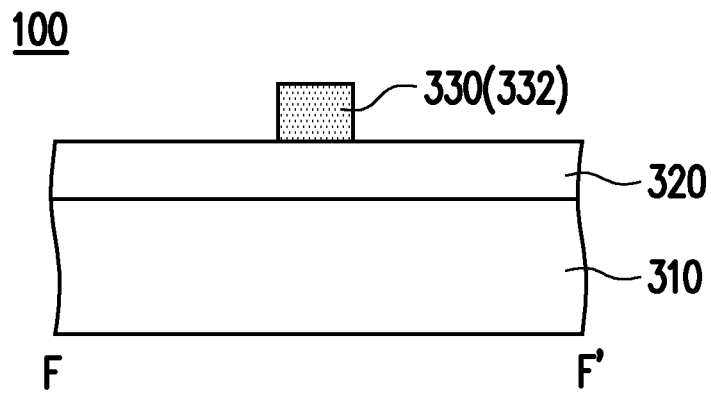


FIG. 8C

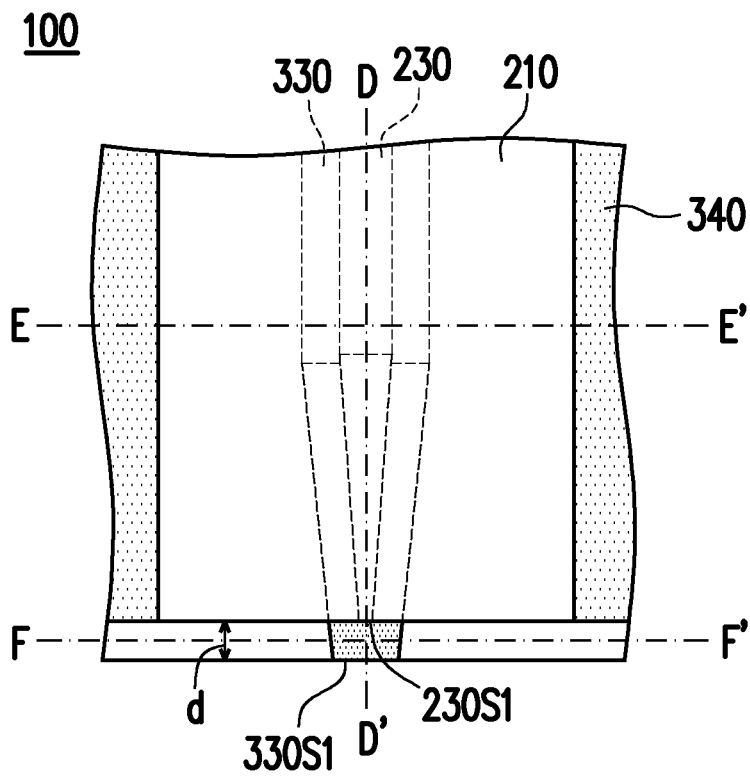


FIG. 8D

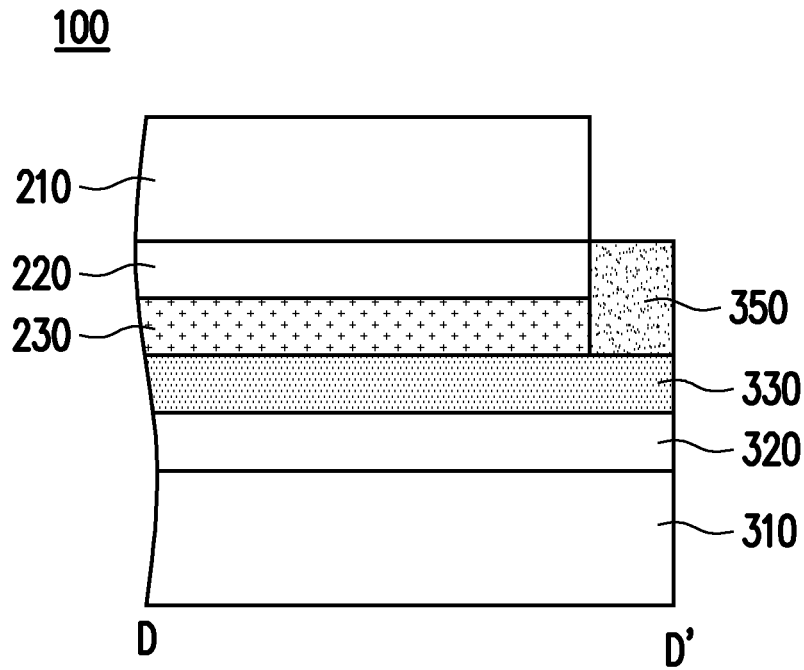


FIG. 9A

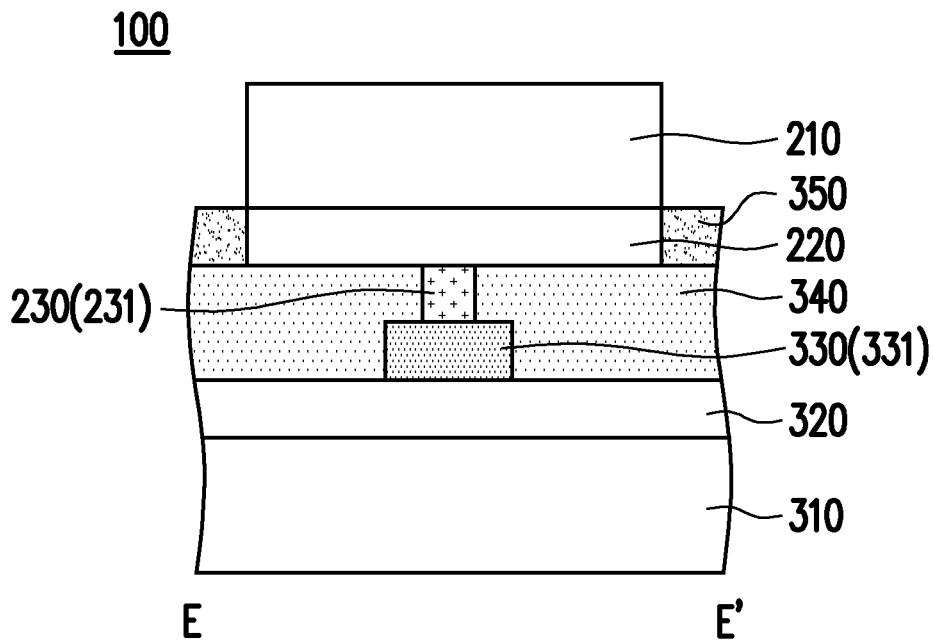


FIG. 9B



100

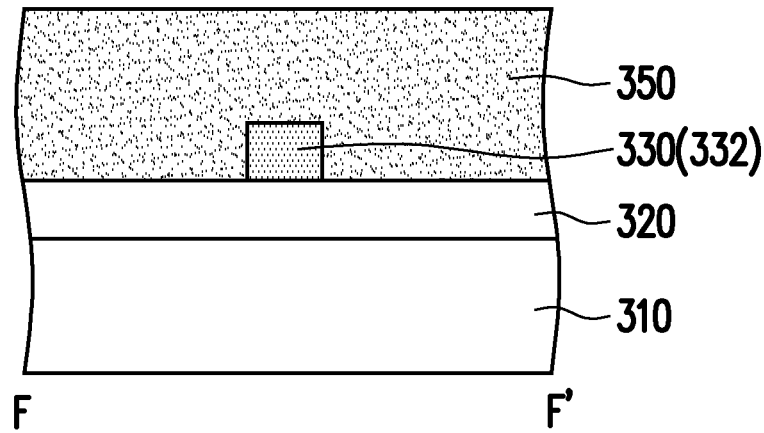


FIG. 9C

100

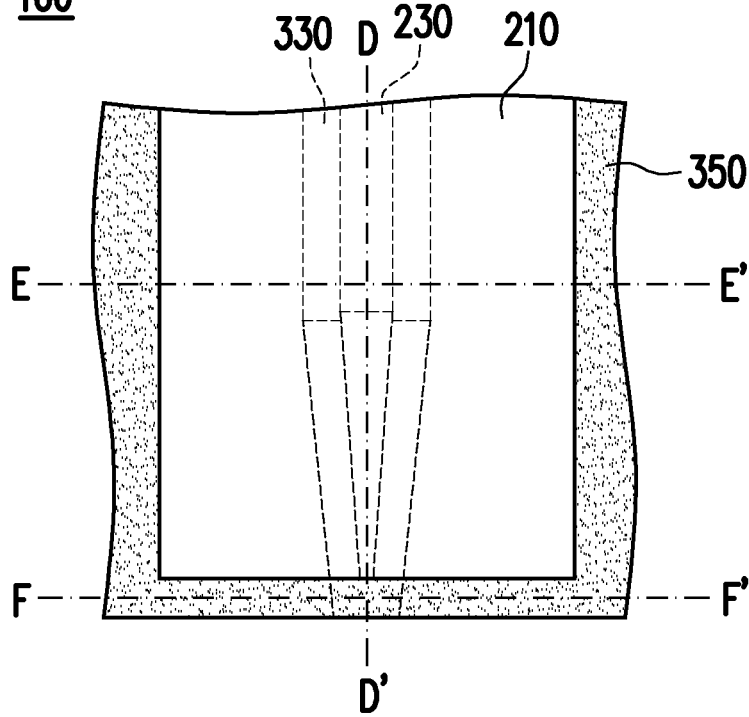


FIG. 9D

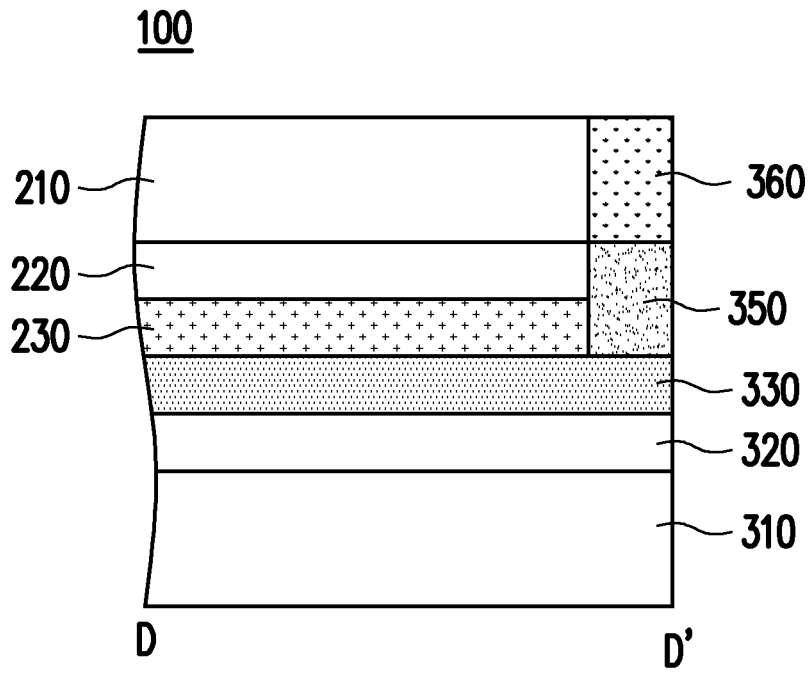


FIG. 10A

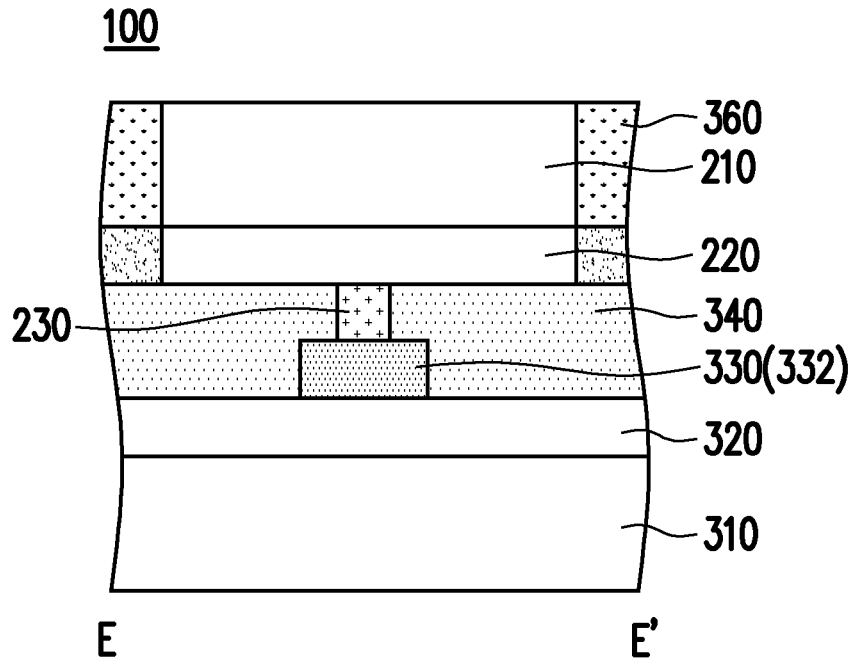


FIG. 10B

100

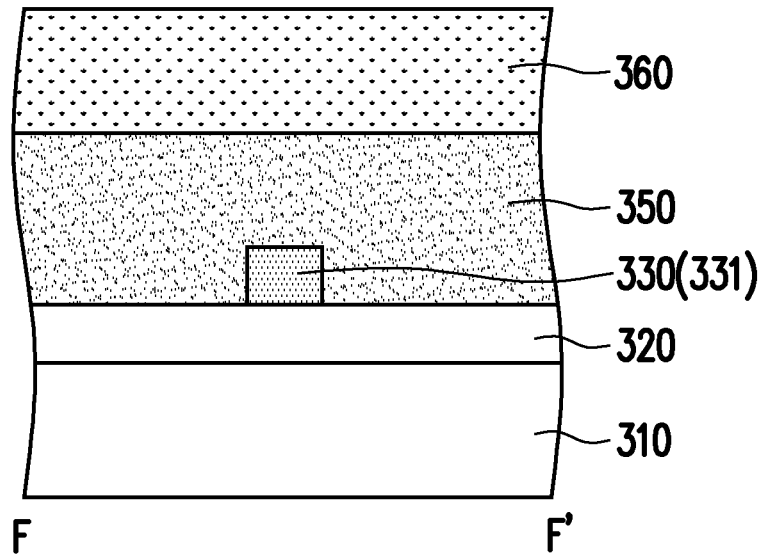


FIG. 10C

100

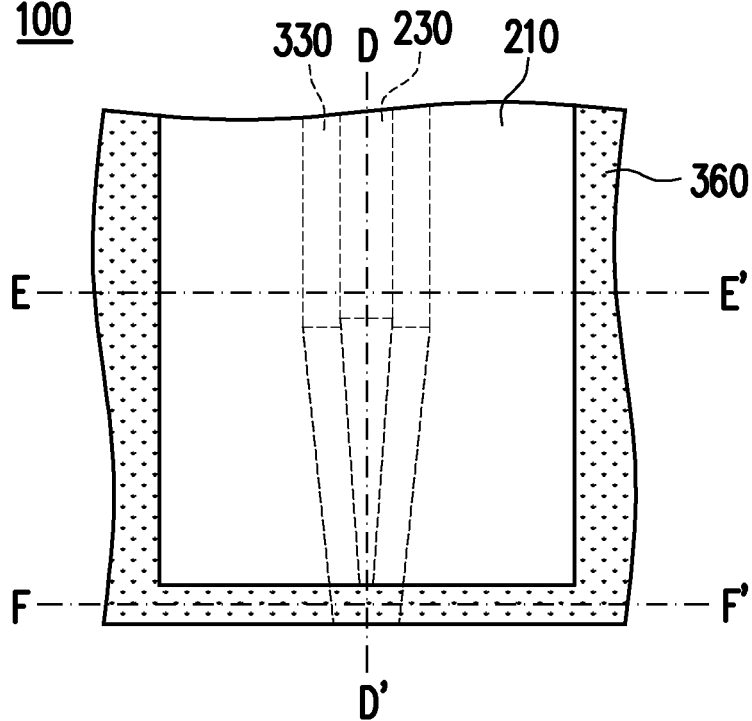


FIG. 10D

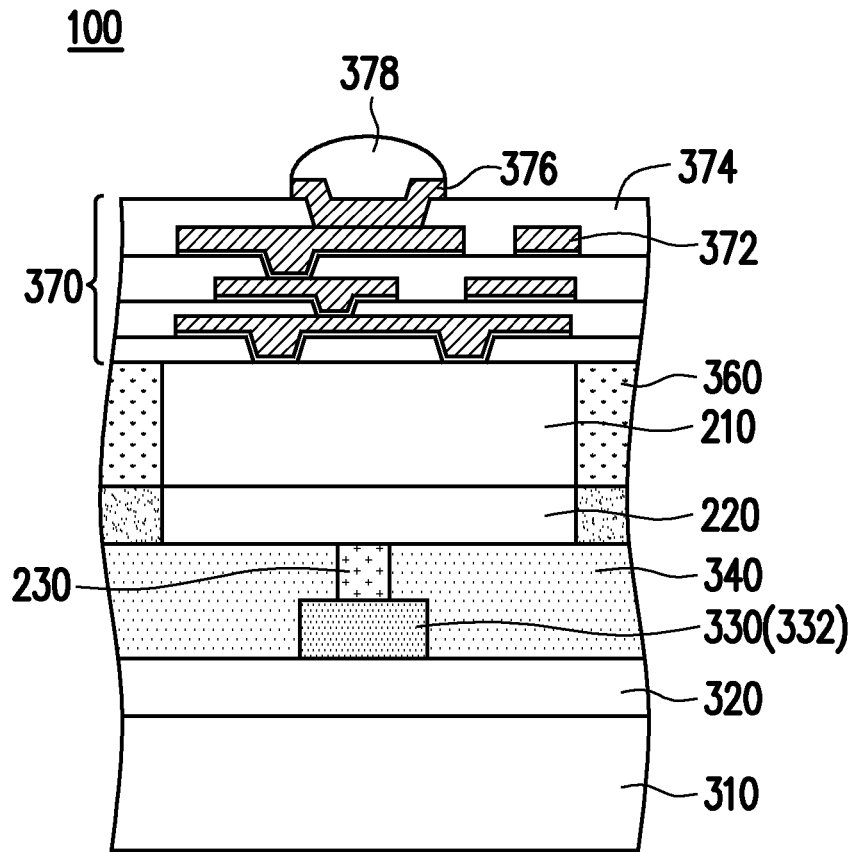


FIG. 11

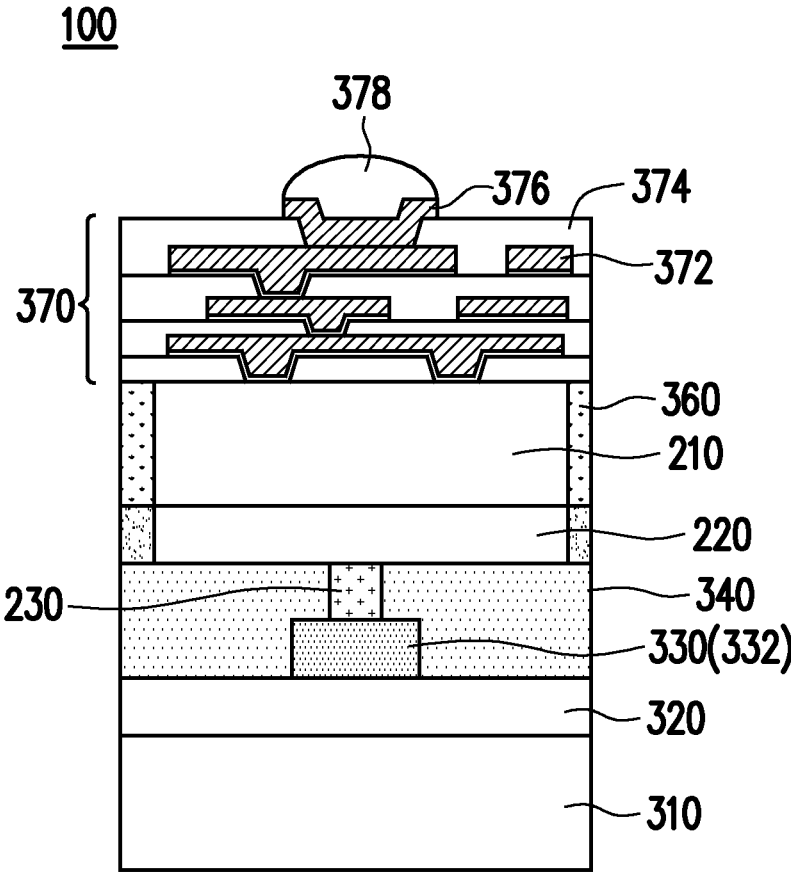


FIG. 12

## OPTICAL SYSTEM

## CROSS-REFERENCE TO RELATED APPLICATION

This application is a divisional application of and claims the priority benefit of a prior application Ser. No. 17/140,134, filed on Jan. 4, 2021. The entirety of the above-mentioned patent application is hereby incorporated by reference herein and made a part of this specification.

## BACKGROUND

The growth of the internet and network traffic rate is pushing a demand for optical-based data communication. Many of optical components used in the optical-based data communication systems may be fabricated in semiconductor devices, and may be further integrated as a silicon photonic integrated chips (PIC) for high-speed optical interconnects. The optical signal is typically transmitted from an optical fiber to PIC through a silicon waveguide. However, the size of the silicon waveguide in a PIC is typically much smaller than the core diameter of an optic fiber, which may lead to a significant signal loss. It is important to properly direct the optical signal from the optical fiber to the silicon waveguide and vice versa without significant signal loss.

## BRIEF DESCRIPTION OF THE DRAWINGS

Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is noted that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

FIG. 1 is a schematic view of an optical system according to some exemplary embodiments of the present disclosure.

FIGS. 2A and 2B are top view and side view of a portion of the optical coupler according to some exemplary embodiments of the present disclosure.

FIG. 3A to FIG. 12 are schematic cross-sectional views of various stages in a manufacturing method of an optical coupler according to some exemplary embodiments of the present disclosure.

## DETAILED DESCRIPTION

The following disclosure provides many different embodiments, or examples, for implementing different features of the provided subject matter. Specific examples of components, values, operations, materials, arrangements, or the like, are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. Other components, values, operations, materials, arrangements, or the like, are contemplated. For example, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed between the first and second features, such that the first and second features may not be in direct contact. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of

simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed.

Further, spatially relative terms, such as “beneath,” “below,” “lower,” “above,” “upper” and the like, may be used herein for ease of description to describe one element or feature’s relationship to another element(s) or feature(s) as illustrated in the figures. The spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. The apparatus may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein may likewise be interpreted accordingly.

In addition, terms, such as “first”, “second”, “third” and the like, may be used herein for ease of description to describe similar or different element(s) or feature(s) as illustrated in the figures, and may be used interchangeably depending on the order of the presence or the contexts of the description.

Other features and processes may also be included. For example, testing structures may be included to aid in the verification testing of the 3D packaging or 3DIC devices. The testing structures may include, for example, test pads formed in a redistribution layer or on a substrate that allows the testing of the 3D packaging or 3DIC, the use of probes and/or probe cards, and the like. The verification testing may be performed on intermediate structures as well as the final structure. Additionally, the structures and methods disclosed herein may be used in conjunction with testing methodologies that incorporate intermediate verification of known good dies to increase the yield and decrease costs.

FIG. 1 is a schematic view of an optical system 1. The optical system 1 includes an optical device 10. In some embodiments, the optical device 10 is a photonic integrated chip (PIC) or the like. The optical system further includes an optical source 20. In some embodiments, the optical source 20 is a laser source or the like. The optical system 1 further includes an optical fiber 30, wherein one end of the optical fiber 30 connects with the optical source 20, and the other end of the optical fiber 30 connects with the optical coupler 100 of the optical device 10. When an optical signal is generated from the optical source 20, the optical signal is transmitted to the optical coupler 100 of the optical device 10 through the optical fiber 30. The optical coupler 100 receives the optical signal from the optical fiber 30 and transmits the optical signal to the optical device 10.

In some situations, the width of the optical fiber 30 is about 9  $\mu\text{m}$ , and the width of a typical silicon waveguide in an optical device is about 0.2  $\mu\text{m}$ , which is much smaller than the width of the optical fiber 30. When the optical signal is transmitted from the optical fiber 30 to the silicon waveguide of the optical device 10, since the width of the silicon waveguide is much smaller than the width of the optical fiber 30, there may be a significant signal loss when transmitting the optical signal from the optical fiber 30 to the optical device 10.

In order to reduce the signal loss when transmitting the optical signal from the optical fiber 30 to the optical device 10, the optical signal is first received by the optical coupler 100. The optical coupler 100 includes two optical waveguides. The first waveguide of the optical coupler 100, which has a width substantially the same as the optical fiber 30, receives the optical signal from the optical fiber 30. Since the width of the first waveguide of the optical coupler 100 is compatible to the width of the optical fiber, the signal loss between the optical fiber 30 and the optical coupler 100

is significantly reduced. The optical signal received by the first waveguide of the optical coupler **100** is then coupled to the second waveguide, and further transmits to the optical device **10** through adiabatic coupling. Specifically, the second waveguide is part of the photonic IC, which is a silicon waveguide, the width of the second waveguide of the optical coupler **100** is compatible to the width of the silicon waveguide of the optical device **10**. Therefore, the optical signal may be easily transmitted to the optical device through the second waveguide. As a result, a signal loss due to the mismatch between the width of the optical fiber **30** and the width of the silicon waveguide in the optical device **10** may be significantly reduced by the optical coupler **100**.

FIGS. **2A** and **2B** illustrate a portion of the optical coupler **100**. FIG. **2A** is a top view of a portion of the optical coupler **100**. FIG. **2B** is a side view of a portion of the optical coupler **100**. Some components of the optical coupler **100** are not illustrated in FIGS. **2A** and **2B** for clarity.

The optical coupler **100** includes a first waveguide **330** and a second waveguide **230**. As shown in FIGS. **2A** and **2B**, the second waveguide **230** is disposed on the first waveguide **330**. The overlapped portions the first waveguide **330** and the second waveguide **230** may also be referred as coupling portions of the first waveguide **330** and the second waveguide **230**. The coupling portion of second waveguide **230** is optically coupled to the coupling portion of the first waveguide **330**. The coupling portion of the first waveguide **330** includes a straight part **331** and a taper part **332**. The coupling portion of the second waveguide **230** includes a straight part **231** and a taper part **232**. The taper part **232** of the second waveguide **230** is optically coupled with the taper part **332** of the first waveguide **330**. The straight part **231** of the second waveguide **230** is optically coupled with the straight part **331** of the first waveguide **330**.

When an optical signal enters the optical coupler **100**, the optical signal will first enter the optical coupler **100** through the taper part **332** of the first waveguide **330**. Then the optical signal in the taper part **332** of the first waveguide **330** is then optically coupled and transferred to the taper part **232** of the second waveguide **230** through adiabatic optical coupling.

In the adiabatic optical process, the geometrical changes of the taper part **332** of the first waveguide **330** and the taper part **232** of the second waveguide **230** are sufficient gradual, such that no energy is transferred from the incoming mode of the optical signal to other modes of the optical signal. In other words, the fundamental-order mode of the optical signal propagates through the structures such as the taper part **332** of the first waveguide **330** and the taper part **232** of the second waveguide **230** without transfer of power to any higher-order guided or radiative modes. As a result, the optical signal received by the optical coupler **100** may be lossless in the optical coupler **100**.

In some embodiments, a material of the first waveguide **330** includes a polymer material, such as siloxane-based polymers, or include a combination of polymer materials, such as poly(methylmethacrylate) (PMMA), polystyrene (PS), polycarbonate, polyurethane, benzocyclo butane, perfluorovinyl ether cyclopolymer, tetrafluoroethylene, perfluorovinyl ether copolymer, silicone, fluorinated poly(arylene) ether sulfide, poly(pentafluorostyrene), fluorinated dendrimers, fluorinated hyperbranched polymers, or the like. In some embodiments, a material of the second waveguide **230** includes doped silicon, undoped silicon, silicon nitride, silicon oxynitride or the like. In some embodiments, the index of refraction of the material of the first waveguide **330** is between 1.5 to 1.8. In some embodiments, the index of

refraction of the material of the second waveguide **230** is between 3.4 to 3.6. Referring to FIG. **2B**, in some embodiments the thickness **T1** of the first waveguide **330** is between 2  $\mu\text{m}$  to 6  $\mu\text{m}$ . In some embodiments, the thickness **T1** of the first waveguide **330** is larger than 3  $\mu\text{m}$ . In some embodiments the thickness **T2** of the second waveguide **230** is between 200 nm to 500  $\mu\text{m}$ . In some embodiments, the thickness **T2** of the second waveguide **230** is larger than 270 nm.

The taper part **332** of the first waveguide **330** has a wider end **330S2** and a narrower end **330S1**. The wider end **330S2** of the taper part **332** of the first waveguide **330** has a width **W11**, and the narrower end **330S1** of the taper part **332** of the first waveguide **330** has a width **W21**. The length of the taper part **332** of the first waveguide **330** is **L21**.

The straight part **331** of the first waveguide **330** connects with the wider end **330S2** of the taper part **332**. In some embodiments, the straight part **331** of the first waveguide **330** has a constant width, wherein the width of one end **330S2** of the straight part **331** of the first waveguide **330** has a same width of the other end **330S3** of the straight part **331** of the first waveguide **330**, which is **W11**, equal to the width of the wider end of the taper part **332** of the first waveguide **330**. The straight part **331** of the first waveguide **330** has a length **L11** and a width **W11**.

The taper part **232** of the second waveguide **230** has a wider end **230S2** and a narrower end **230S1**. The wider end **230S2** of the taper part **232** of the second waveguide **230** has a width **W12**, and the narrower end **230S1** of the taper part **232** of the second waveguide **230** has a width **W22**. The length of the taper part **232** of the second waveguide **230** is **L22**.

The straight part **231** of the second waveguide **230** connects with the wider end **230S2** of the taper part **232**. In some embodiments, the straight part **231** of the second waveguide **230** has a constant width, wherein the width of one end **230S2** of the straight part **231** of the second waveguide **230** has a same width of the other end **230S3** of the straight part **231** of the second waveguide **230**, which is **W12**, equal to the width of the wider end of the taper part **232** of the second waveguide **230**. The straight part **231** of the second waveguide **230** has a length **L12** and a width **W12**.

In some embodiments, the total length of the second waveguide **230**, which is the length **L12** of the straight part **231** and the length **L22** of the taper part **232**, is smaller than the total length of the first waveguide **330**, which is the length **L11** of the straight part **331** and the length **L21** of the taper part **332**.

In some embodiments, the width **W12** of the end **230S3** the straight part **231** of the second waveguide **230** is smaller than the width **W11** of the end **330S3** of the straight part **331** of the first waveguide **330**. In some embodiments, the width **W22** of the narrower end **230S1** of the taper part **232** of the second waveguide **230** is smaller than the width **W21** of the narrower end **330S1** of the taper part **332** of the first waveguide **330**.

In some embodiments, the narrower end **230S1** of the taper part **232** of the second waveguide **230** is separated from the narrower end **330S1** of the taper part **332** of the first waveguide **330** by a distance **d**. In some embodiments, the distance **d** is between 0  $\mu\text{m}$  to 500  $\mu\text{m}$ .

In some embodiments, the optical signal is transmitted between the first waveguide **330** and the second waveguide **230** through the adiabatic optical process. In some embodiment, in the first waveguide **330**, the width **W11** of the end **330S3** of the straight part **331** is between 1  $\mu\text{m}$  to 10  $\mu\text{m}$ . In

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some embodiments, the width  $W_{11}$  of the end **330S3** of the straight part **331** is larger than  $3\ \mu\text{m}$ . In some embodiment, the minimum width  $W_{21}$  of the narrower end **330S1** of the taper part **332** is between  $200\ \text{nm}$  to  $5000\ \text{nm}$  (i.e.  $5\ \mu\text{m}$ ). In some embodiment, the minimum width  $W_{21}$  of the narrower end **330S1** of the taper part **332** is larger than  $1.6\ \mu\text{m}$ . In some embodiments, the length  $L_{11}$  of the straight part **331** is between  $500\ \mu\text{m}$  to  $5000\ \mu\text{m}$ . In some embodiments, the length  $L_{11}$  of the straight part **331** is larger than  $500\ \mu\text{m}$ . In some embodiments, the length  $L_{21}$  of the taper part **332** is between  $100\ \mu\text{m}$  to  $5000\ \mu\text{m}$ . In some embodiments, the length  $L_{21}$  of the taper part **332** is smaller than  $500\ \mu\text{m}$ . In some embodiments, for broadband optical signal transmission, such as the optical signal having wavelength between  $126\ \text{nm}$  to  $136\ \text{nm}$ , the total length of the first waveguide **330**, which is total the length of the taper part **332** and the straight part **331**, is less than  $1000\ \mu\text{m}$ .

In some embodiments, in the first waveguide **330**, a ratio of the length  $L_{11}$  of the straight part **331** to the length  $L_{21}$  of the taper part **332** is between 1:1 to 4:1. In some embodiments, in the first waveguide **330**, a ratio of the width  $W_{21}$  of the narrower end **330S1** of the taper part **332** to the length  $L_{21}$  of the taper part **332** is between 1.6:500 to 1.6:5000.

In some embodiment, in the second waveguide **230**, the width  $W_{12}$  of the end **230S3** of the straight part **231** is between  $0.2\ \mu\text{m}$  to  $5\ \mu\text{m}$ . In some embodiment, in the second waveguide **230**, the width  $W_{12}$  of the end **230S3** of the straight part **231** is larger than  $0.2\ \mu\text{m}$ . In some embodiment, the width  $W_{22}$  of the narrower end **230S1** of the taper part **232** is between  $60\ \text{nm}$  to  $5000\ \text{nm}$  (i.e.  $5\ \mu\text{m}$ ). In some embodiment, the minimum width  $W_{22}$  of the narrower end **230S1** of the taper part **232** is larger than  $60\ \text{nm}$ . In some embodiments, the length  $L_{12}$  of the straight part **231** is between  $500\ \mu\text{m}$  to  $5000\ \mu\text{m}$ . In some embodiments, the length  $L_{12}$  of the straight part **231** is larger than  $500\ \mu\text{m}$ . In some embodiments, the length  $L_{22}$  of the taper part **232** is between  $100\ \mu\text{m}$  to  $5000\ \mu\text{m}$ . In some embodiments, the length  $L_{22}$  of the taper part **232** is smaller than  $500\ \mu\text{m}$ . In some embodiments, for broadband optical signal transmission, such as the optical signal having wavelength between  $126\ \text{nm}$  to  $136\ \text{nm}$ , the total length of the silicon waveguide **230**, which is total the length of the taper part **232** and the straight part **231**, is less than  $1000\ \mu\text{m}$ .

In some embodiments, in the second waveguide **230**, a ratio of the length  $L_{12}$  of the straight part **231** to the length  $L_{22}$  of the taper part **232** is between 1:1 to 3.99:1, and a ratio of the width  $W_{22}$  of the narrower end **230S1** of the taper part **232** to the length  $L_{22}$  of the taper part **232** is between 1.6:499 to 1.6:4999.

In some embodiments, a ratio of a length  $L_{21}$  of the taper part **332** of the first waveguide **330** to a length  $L_{22}$  of the taper part **232** of the second waveguide **230** is smaller than or substantially equal to 3:1.

In some embodiments, a longitudinal axis of the second waveguide **230** and a longitudinal axis of the first waveguide **330** are substantially aligned from a top view of the optical coupler **100**. In some embodiments, the offset between the longitudinal axis of the second waveguide **230** and the longitudinal axis of the first waveguide **330** from the top view is less than  $5\ \mu\text{m}$ . With the second waveguide **230** and the first waveguide **330** substantially aligned with each other, the optical signal may be transmitted between the two waveguides more efficiently and with less signal loss.

FIGS. **3A** to **3C** and FIGS. **4A** to **4D** show a process for forming a waveguide **230**, in accordance with some embodiments. FIG. **3A** and FIG. **3B** are cross-sectional views of

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FIG. **3C** along line AA' and line BB' and FIG. **3C** is a top view of an optical structure **200**. Referring to FIGS. **3A** to **3C**, a substrate **210** is provided. A dielectric layer **220** is formed over the substrate **210**. A silicon layer **228** is formed over the dielectric layer **220**. In some embodiments, the substrate **210** is a material such as a glass, ceramic, dielectric, or a semiconductor substrate. In some embodiments, the substrate **210** includes a bulk semiconductor or the like, which is doped (e.g., with a p-type or an n-type dopant) or undoped. In some embodiments, the substrate **210** is a wafer, such as a silicon wafer or other type of semiconductor wafer. Other substrate materials, such as a multi-layered or gradient substrate may also be used. In some embodiments, the material of the substrate **210** include silicon, germanium, a compound semiconductor including silicon carbide, gallium arsenic, gallium phosphide, indium phosphide, indium arsenide, and/or indium antimonide, an alloy semiconductor including SiGe, GaAsP, AlInAs, AlGaAs, GaInAs, GaInP, and/or GaInAsP, the like, or combinations thereof. In some embodiments, the substrate **210** is a silicon photonic integrated chip (PIC) including electrical circuitries and at least one waveguide. In some embodiments, the dielectric layer **220** is an oxide layer. In some embodiments, the dielectric layer **220** is a silicon oxide or the like. In some embodiments, the dielectric layer **220** is also referred as an oxide layer **220**. In some embodiments, the dielectric layer has a thickness between about  $2\ \mu\text{m}$  to about  $3\ \mu\text{m}$ . The silicon layer **228** includes doped silicon, undoped silicon, silicon nitride, silicon oxynitride or the like. In some embodiments, the silicon layer **228** has a thickness between about  $200\ \text{nm}$  to about  $500\ \text{nm}$ . In some embodiments, the silicon layer has a thickness larger than  $270\ \text{nm}$ . In some embodiments, the substrate **210**, the dielectric layer **220**, and the silicon layer **228** is formed as a buried oxide ("BOX") substrate.

FIG. **4A**, FIG. **4B** and FIG. **4C** are cross-sectional views of FIG. **4D** along line AA', line BB', and line CC', and FIG. **4D** is a top view of the optical structure **200**. Referring to FIGS. **4A** to **4D**, the silicon layer **228** is patterned to form the silicon waveguide **230**. The silicon layer **228** may be patterned by using photolithography and etching techniques. In some embodiments, a hard-mask layer (e.g., a nitride layer or other dielectric material, not shown in FIGS. **4A** to **4D**) is formed over the silicon layer **228** and be patterned. The pattern of the hard-mask layer may then be transferred to the silicon layer **228** using one or more etching techniques. In some embodiments, the etching technique includes dry etching and/or wet etching techniques. In some embodiments, more than one photolithography and etching sequence are used in order to pattern the silicon layer **228** into a silicon waveguide **230**.

As shown in FIGS. **4B**, **4C** and **4D**, the waveguide **230** includes a straight part **231** and a taper part **232**. The taper part **232** has a wider end **230S2** and a narrower end **230S1**. The wider end **230S2** of the taper part **232** has a width  $W_{12}$ , and a narrower end **230S1** of the taper part **232** has a width  $W_{22}$ . A length of the taper part **232** is  $L_{22}$ . One end of the straight part **231** connects with a wider end **230S2** of the taper part **232**, and a width of the other end **230S3** of the straight part **231** is  $W_{12}$ , which is the same as the width of the wider end **230S2** of the taper part **232**. A length of the straight part **231** is  $L_{12}$ .

Referring to FIGS. **4B** and **4C**, line BB' crosses the straight part **231** and line CC' crosses the taper part **232**. As a result, the width of the waveguide **230** in FIG. **4B**, which is the width of the straight part **231**, is wider than the width of the waveguide **230** in FIG. **4C**, which is the width of the taper part **232**.



In some embodiment, the width **W12** of the end **230S3** of the straight part **231** is larger than 0.2  $\mu\text{m}$ . In some embodiment, the width **W22** of the narrower end **230S1** of the taper part **232** is between 60 nm to 5000 nm (i.e. 5  $\mu\text{m}$ ). In some embodiment, the minimum width **W22** of the narrower end **230S1** of the taper part **232** is larger than 60 nm. In some embodiment, the length **L12** of the straight part **231** is between 500  $\mu\text{m}$  to 5000  $\mu\text{m}$ . In some embodiment, the length **L12** of the straight part **231** is larger than 500  $\mu\text{m}$ . In some embodiment, the length **L22** of the taper part **232** is between 100  $\mu\text{m}$  to 5000  $\mu\text{m}$ . In some embodiment, the length **L22** of the taper part **332** is smaller than 500  $\mu\text{m}$ . In some embodiment, for broadband optical signal transmission, such as the optical signal having wavelength between 126 nm to 136 nm, the total length of the waveguide **230**, which is total the length of the taper part **232** and the straight part **231**, is less than 1000  $\mu\text{m}$ .

After the waveguide **230** is patterned, a singulation step is performed on the wafer to separate the wafer into a plurality of photonic IC dies. In some embodiment, the singulation process includes sawing, laser ablation, etching, a combination thereof, or the like.

FIG. 5A and FIG. 5B are cross-sectional views of FIG. 5C along line DD' and line EE' and FIG. 5C is a top view of an optical structure **300**. Referring to FIG. 5A to FIG. 5C, a substrate **310** is provided. In some embodiment, the material of the substrate **310** includes materials such as silicon, silicon oxide, gallium arsenide, silicon nitride, glass, quartz, plastics, ceramics, crystalline materials and the like.

A cladding layer **320** is formed over the substrate **310**. In some embodiment, the cladding layer **320** is made of silicon resin, which is an optical resin and forms a transparent layer. The refractive index of the cladding layer **320** is lower than the refractive index of the core layer **328**. In some embodiment, the material of the cladding layer **320** includes materials such as silicon resins, polysiloxanes, fluorinated polysiloxanes, with fluorinated substituents such as methyl groups or phenyl groups, or the like. In some embodiment, the cladding layer **320** is formed on the substrate **310** through doctor-blade coating, or spin-coating or other suitable methods. After the cladding layer **320** is deposited on the substrate **310**, the cladding layer **320** is exposed with radiation, such as ultra-violet (UV) light to cure the cladding layer **320**.

After the cladding layer **320** is formed on the substrate **310**, a waveguide core layer **328** is formed on the under cladding layer **320**. In some embodiment, the material of the core layer **328** depends on the optical bands the waveguide to be operated. In some embodiment, the core layer **328** is designed to operate in the O-band (around  $\lambda=1310$  nm) and C-band (around  $\lambda=1550$  nm). In some embodiment, the material of the core layer **328** includes silioxane-based polymers. In some embodiment, the material of the core layer **328** includes a combination of polymer materials, such as poly(methylmethacrylate) (PMMA), polystyrene (PS), polycarbonate, polyurethane, benzocyclo butane, perfluorovinyl ether cyclopolymer, tetrafluoroethylene, perfluorovinyl ether copolymer, silicone, fluorinated poly(arylene) ether sulfide, poly(pentafluorostyrene), fluorinated dendrimers, fluorinated hyperbranched polymers, or the like. In some embodiment, the core layer **328** is formed on the cladding layer **320** through doctor-blade coating, or spin-coating or other suitable methods. In some embodiment, the material of the core layer **328** is selected to have an index of refraction larger than the index of refraction of the cladding layer **320** to ensure the proper light propagation of the polymer waveguide **330** which will be formed in later steps.

In some embodiment, the difference of the index of refraction ( $\Delta n$ ) between the core layer **328** and the cladding layer **320** is between 0.005 to 0.008. In some embodiment, a thickness of the core layer **328** is between 2  $\mu\text{m}$  to 6  $\mu\text{m}$ . In some embodiment, the thickness of the core layer **328** is larger than 3  $\mu\text{m}$ .

FIG. 6A, FIGS. 6B and 6C are cross-sectional views of FIG. 6D along line DD', line EE' and line FF', and FIG. 6D is a top view of the optical structure **300**. Referring to FIGS. 6A to 6D, after the core layer **328** is deposited on the cladding layer **320**, the core layer **328** is patterned to form the waveguide **330**. In some embodiment, the core layer **328** is patterned through a UV-laser direct writing process, or a proximity-mask-lithography or other suitable methods.

After the patterning process, the patterned core layer **328** is treated with a solvent-based wet-chemical development process to develop the pattern of the core layer **328** and remove the unwanted portions of the core layer **328**. After the patterning and developing process, the core layer **328** becomes the waveguide **330**, as shown in FIGS. 6A to 6D.

As shown in FIGS. 6B, 6C and 6D, the waveguide **330** includes a straight part **331** and a taper part **332**. The taper part **332** has a wider end **330S2** and a narrower end **330S1**. The wider end **330S2** of the taper part **332** has a width **W11**, and a narrower end **330S1** of the taper part **332** has a width **W21**. A length of the taper part **332** is **L21**. One end of the straight part **331** connects with the wider end **330S2** of the taper part **332**, and a width of the other end **330S3** of the straight part **331** is **W11**, which is the same as the width of the wider end **330S2** of the taper part **332**. A length of the straight part **331** is **L11**.

FIGS. 6B and 6C are cross-sectional views of the line EE' and line FF' of the waveguide **330** in FIG. 6D. Referring to FIGS. 6B and 6C, line EE' crosses the straight part **331** and line FF' crosses the taper part **332**. As a result, the width of the waveguide **330** in FIG. 6B, which is the width of the straight part **331**, is wider than the width of the waveguide **330** in FIG. 6C, which is the width of the taper part **332**.

In some embodiment, the width **W11** of the end **330S3** of the straight part **331** is between 1  $\mu\text{m}$  to 10  $\mu\text{m}$ . In some embodiment, the width **W11** of the end **330S3** of the straight part **331** is larger than 3  $\mu\text{m}$ . In some embodiment, the minimum width **W21** of the narrower end **330S1** of the taper part **332** is between 200 nm to 5000 nm (i.e. 5  $\mu\text{m}$ ). In some embodiment, the minimum width **W21** of the narrower end **330S1** of the taper part **332** is larger than 1.6  $\mu\text{m}$ . In some embodiment, the length **L11** of the straight part **331** is between 500  $\mu\text{m}$  to 5000  $\mu\text{m}$ . In some embodiment, the length **L11** of the straight part **331** is larger than 500  $\mu\text{m}$ . In some embodiment, the length **L21** of the taper part **332** is between 100  $\mu\text{m}$  to 5000  $\mu\text{m}$ . In some embodiment, the length **L21** of the taper part **332** is smaller than 500  $\mu\text{m}$ . In some embodiment, for broadband optical signal transmission, such as the optical signal having wavelength between 126 nm to 136 nm, the total length of the waveguide **330**, which is total the length of the taper part **332** and the straight part **331**, is less than 1000  $\mu\text{m}$ .

FIG. 7A, FIG. 7B and FIG. 7C are cross-sectional views of FIG. 7D along line DD', line EE', and line FF', and FIG. 7D is a top view of the optical structure **300**. Referring to FIGS. 7A to 7D, a layer of optical adhesive **340** is deposited on and partially covers the top surface of the waveguide **330** and the cladding layer **320**. As shown in FIGS. 7B and 7D, the optical adhesive **340** covers the straight part **331** of the waveguide **330**, and partially covers the taper part **332** of the waveguide **330**. As shown in FIGS. 7C and 7D, the optical adhesive **340** partially covers the taper part **332** of the

waveguide 330. The wider end 330S2 of the taper part 332 is covered by the optical adhesive 340, and the narrower end 330S1 of the taper part 332 is not covered by the optical adhesive 340. The thickness of the optical adhesive 340 is substantially the same as the total thickness of the thickness of the waveguide 330 and the waveguide 230. In some embodiments, the optical adhesive 340 is polyimide or oxide. The index of refraction of the optical adhesive 340 is smaller than the index of refraction of the waveguide 330 and the waveguide 230.

Referring to FIGS. 8A to 8D, FIG. 8A, FIG. 8B and FIG. 8C are cross-sectional views of FIG. 8D along line DD', line EE', and line FF', and FIG. 8D is a top view of an optical coupler 100. The optical structure 200, as shown in FIGS. 4A to 4D, is disposed on the optical structure 300 through a flip-chip method. The optical structure 200 is flipped and the waveguide 230 of the optical structure 200 is disposed on and optically coupled with the waveguide 330 of the optical structure 300. From the top view of the optical coupler 100, the area of the substrate 210 of the optical structure 200 is smaller than the substrate 310, wherein portions of the top surface of the optical adhesive 340 are uncovered by the optical structure 200.

After the optical structure 200 is disposed on the optical coupler 100, the optical adhesive 340 fills the spaces between the cladding layer 320 and the dielectric layer 220. The optical adhesive 340 also surrounds the sidewall of the waveguide 230. Then, the optical coupler 100 is exposed with UV to cure the optical adhesive 340. After curing the optical adhesive 340, the optical structure 200 is firmly attached on the optical coupler 100, and the waveguide 230 is attached on and optically coupled with the waveguide 330. In some embodiments, the cured optical adhesive 340 is also referred as a cladding layer 340.

When disposing the waveguide 230 on the waveguide 330, a longitudinal axis of the waveguide 230 and a longitudinal axis of the waveguide 330 are substantially aligned from a top view of the optical coupler 100. In some embodiments, the offset between the longitudinal axis of the waveguide 230 and the longitudinal axis of the waveguide 330 from the top view is less than 5  $\mu\text{m}$ . With the waveguide 230 and the waveguide 330 substantially aligned with each other, the optical signal may be transmitted between the two waveguides more efficiently and with less signal loss.

In some embodiments, when disposing the waveguide 230 on the waveguide 330, the narrower end 230S1 of the taper part 232 of the waveguide 230 is separated from the narrower end 330S1 of the taper part 332 of the waveguide 330 by a distance d. In some embodiments, the distance d is between 0  $\mu\text{m}$  to 500  $\mu\text{m}$ .

Referring to FIGS. 9A to 9D, FIG. 9A, FIG. 9B and FIG. 9C are cross-sectional views of FIG. 9D along line DD', line EE', and line FF', and FIG. 9D is a top view of an optical coupler 100. A cladding layer 350 is formed on the exposed portion of the cured optical adhesive 340, the exposed portion of the cladding layer 320, and the exposed portion of the taper part 332 of the waveguide 330, which are not covered by the optical structure 200. The material of the formation methods of the cladding layer 350 are similar to the processes for forming the cladding layer 320 as described in FIGS. 5A to 5B, and thus may not be repeated herein. In some embodiments, the material of the cladding layer 350 and the material of the cladding layer 320 are the same. In some embodiments, the material of the cladding layer 350 and the material of the cladding layer 320 are different.

As shown in FIG. 9B, which is the cross-sectional view along the line EE' of FIG. 9D, the cladding layer is formed on the optical adhesive 340, and encloses the dielectric layer 220. As shown in FIG. 9B, the top surface of the cladding layer 350 is substantially coplanar with the top surface of the dielectric layer 220. In some embodiments, the top surface of the cladding layer 350 is above the top surface of the dielectric layer 220 and below the top surface of the substrate 210. In some embodiments, the top surface of the cladding layer 350 is below the top surface of the dielectric layer 220.

As shown in FIG. 9C, which is the cross-sectional view along the line FF' of FIG. 9D, the cladding layer 350 is formed on the exposed portion of cladding layer 320, and on the portion of the taper part 332 of the waveguide 330 which is not covered by the optical structure 200.

Referring to FIGS. 10A to 10D, FIG. 10A, FIG. 10B and FIG. 10C are cross-sectional views of FIG. 10D along line DD', line EE', and line FF', and FIG. 9D is a top view of an optical coupler 100. A molding compound 360 is disposed on the top surface of the substrate 210 and the cladding layer 350. In some embodiments, the material of the molding compound 360 includes an epoxy, a resin, a moldable polymer, a combination thereof, or the like. In some embodiments, the molding compound 360 is applied while substantially liquid, and then is cured through a chemical reaction, such as in an epoxy or resin. In other embodiments, the molding compound 360 is an ultraviolet (UV) or thermally cured polymer applied as a gel.

After the molding compound 360 is disposed and cured on the top surface of the substrate 210 and the cladding layer 350, the A planarization process is then performed on the molding compound 360 to remove a portion of the molding compound 360, such that the top surfaces of the substrate 210 is exposed. In some embodiments, top surfaces of the substrate 210 and the molding compound 360 are substantially coplanar after the planarization process. In some embodiments, the planarization process is a chemical-mechanical polish (CMP), a grinding process, or the like. In some embodiments, the planarization is omitted if the substrate 210 is already exposed.

In some embodiments, the cladding layer 350 in FIGS. 9A to 9D is omitted, and the cladding layer 350 is replaced by the molding compound 360. The molding compound 360 may be formed on the exposed portion of the cured optical adhesive 340, the exposed portion of the cladding layer 320, and the exposed portion of the taper part 332 of the waveguide 330, which are not covered by the optical structure 200. By replacing the cladding layer 350 with the molding compound 360, the manufacturing process of the optical coupler 100 is simplified.

FIG. 11 is a cross-sectional view of the optical coupler 100. A redistribution layer 370 may be formed on the top surface of the substrate 210. The redistribution layer 370 electrically couples with the substrate 210. In some embodiments, the substrate 210 includes a silicon photonic integrated chip (PIC), and the redistribution layer electrically couples with the PIC in the substrate. As shown in FIG. 11, the redistribution layer 370 includes metallization patterns 372, dielectric layers 372, and under bump metallurgies (UBMs) 376.

After forming the redistribution layer 370, conductive connectors 378 are formed on the redistribution layer 370 and coupled to the redistribution layer 370 through the UBMs 376. The conductive connectors 378 may be ball grid array (BGA) connectors, solder balls, metal pillars, controlled collapse chip connection (C4) bumps, micro bumps,

electroless nickel-electroless palladium-immersion gold technique (ENEPIG) formed bumps, or the like. The conductive connectors include (such as a copper pillar) formed by a sputtering, printing, electro plating, electroless plating, CVD, or the like.

As a result, the external electric signals may be transmitted to or received from the substrate **210** through the connectors **378**, the UBMs **376**, and the redistribution layer **370**.

As illustrated in FIG. **12**, after forming the redistribution layer **370** and the conductive connectors **378** on the substrate **210** and the molding compound **360**, a die-saw (singulation) step is performed on the wafer including substrate **300** to separate the wafer into a plurality of optical coupler **100**. In some embodiments, the singulation process may include sawing, laser ablation, etching, a combination thereof, or the like.

In the embodiment of the present disclosure, an optical coupler is formed by including a tapered waveguide and a tapered silicon waveguide coupled together. With this structure, the length of the optical coupler may be reduced, and the coupling efficiency which couples the optical signal from the waveguide to the silicon waveguide is enhanced. Furthermore, the optical coupler which includes a tapered waveguide and a tapered silicon waveguide coupled together may be adapted in a variety of edge couplers which receives an optical signal from an optical source and transmits the optical signal to the photonic IC. Also, by packaging the silicon photonic chip (such as the optical structure **200**) on the carrier substrate (such as substrate **310**), the formation of the optical coupler may be easily integrated into standard silicon photonic chip processing and packaging.

According to some embodiments, an optical coupler is provided. The optical coupler includes: a first optical structure, and a second optical structure disposed over the first optical structure. The first optical structure includes: a first substrate, a first cladding layer disposed on the first substrate, and a first waveguide disposed on the first cladding layer. The first waveguide includes: a first coupling portion, and the first coupling portion including a first taper part. The second optical structure includes: a second substrate, a dielectric layer disposed on the second substrate, and a second waveguide disposed on the dielectric layer. The second waveguide includes a second coupling portion, and the second coupling portion including a second taper part. The second taper part is disposed on and optically coupled with the first taper part, and a taper direction of the first taper part is the same as a taper direction of the second taper part.

According to some embodiments, an optical system is provided. The optical system includes: an optical source, an optical fiber receiving and transmitting an optical signal from the optical source, and an optical coupler receiving the optical signal from the optical fiber. The optical coupler includes: a first waveguide including a first coupling portion having a first taper part, and a second waveguide disposed on the first waveguide. The second waveguide includes a second coupling portion having a second taper part. The second taper part is disposed on and optically coupled with the first taper part. The first taper part and the second taper part point to the optical fiber.

According to some embodiments, a method of forming an optical coupler, is provided. The method includes: forming a first waveguide on a first substrate, forming a second waveguide on a second substrate, and disposing the second substrate over the first substrate such that the second waveguide is optically coupled with the first waveguide. The first waveguide includes a first coupling portion, and the first

coupling portion includes a first taper part. The second waveguide includes a second coupling portion, and the second coupling portion includes a second taper part. A taper direction of the first taper part is the same as a taper direction of the second taper part.

The foregoing outlines features of several embodiments so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

What is claimed is:

**1.** An optical system, comprising:

an optical source;

an optical fiber receiving and transmitting an optical signal from the optical source; and

an optical coupler receiving the optical signal from the optical fiber, the optical coupler comprising:

a first waveguide comprising a first coupling portion having a first taper part; and

a second waveguide disposed on the first waveguide, the second waveguide comprising a second coupling portion having a second taper part, the second taper part being disposed on and optically coupled with the first taper part,

wherein a thickness of the first waveguide is larger than a thickness of the second waveguide.

**2.** The optical system of claim **1**, wherein the first taper part and the second taper part point to the optical fiber.

**3.** The optical system of claim **1**, wherein an index of refraction of the first waveguide is between 1.5 to 1.8.

**4.** The optical system of claim **1**, wherein the first taper part has a wider end with a first width and a first narrower end with a second width, the first width is between 1  $\mu\text{m}$  to 10  $\mu\text{m}$ , and the second width is between 200 nm to 5  $\mu\text{m}$ .

**5.** The optical system of claim **1**, wherein the second taper part has a wider end with a third width and a second narrower end with a fourth width, the third width is between 0.2  $\mu\text{m}$  to 5  $\mu\text{m}$ , and the fourth width is between 60 nm to 5  $\mu\text{m}$ .

**6.** The optical system of claim **1**, wherein

the first taper part has a first wider end with a first width and a first narrower end with a second width,

the second taper part has a second wider end with a third width and a second narrower end with a fourth width, the third width is smaller than the first width, and the fourth width is smaller than the second width.

**7.** The optical system of claim **1**, wherein a ratio of a length of the first taper part to a length of the second taper part is smaller than or substantially equal to 3:1.

**8.** The optical system of claim **1**, wherein the first waveguide further comprises a first straight part connecting to the first wider end of the first taper part, the second waveguide further comprises a second straight part connecting to the second wider end of the second taper part.

**9.** The optical system of claim **8**, wherein a ratio of a length of the first straight part of the first waveguide to a length of the first taper part of the first waveguide is between 1:1 to 4:1.

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10. The optical system of claim 8, wherein the first straight part has a constant width of the first width, and the second straight part has a constant width of the third width.

11. The optical system of claim 1, wherein a length of the first coupling portion is substantially equal to or longer than a length of the second coupling portion.

12. The optical system of claim 1, wherein a first narrower end of the first taper part is separated from a second narrower end of the second taper part by a nonzero distance.

13. The optical system of claim 1, wherein a longitudinal axis of the first waveguide and a longitudinal axis of the second waveguide are substantially aligned from a top view of the optical coupler.

14. An optical system, comprising:

an optical source;

an optical fiber; and

an optical coupler optically coupled to the optical source through the optical fiber, and the optical coupler comprising:

a first waveguide comprising a first taper part and a first straight part connected to the first taper part; and

a second waveguide disposed on the first waveguide, the second waveguide comprising a second taper part and a second straight part connected to the second taper part, the second taper part being disposed on and optically coupled with the first taper part,

the first taper part comprising a first wider end and a first narrower end opposing to the first wider end, a first width of the first wider end being greater than a second width of the first narrower end,

the second taper part comprising a second wider end and a second narrower end opposing to the second wider end, a third width of the second wider end being greater than a fourth width of the second narrower end,

the third width being different from the first width, and the fourth width being different from the second width,

wherein a thickness of the first waveguide is larger than a thickness of the second waveguide, a first end of the first straight part connects with the first wider end, and a width of the first end of the first straight part is the first width,

wherein a first end of the second straight part connects with the second wider end, and a width of the first end of the second straight part is the third width.

15. The optical system of claim 14, wherein the second straight part is disposed on and optically coupled with the first straight part.

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16. The optical system of claim 14, wherein the third width is smaller than the first width.

17. The optical system of claim 16, wherein the fourth width is smaller than the second width.

18. An optical system, comprising:

an optical source;

an optical fiber; and

an optical coupler optically coupled to the optical source through the optical fiber, and the optical coupler comprising:

a first waveguide comprising a first taper part and a first straight part connected to the first taper part, wherein the first taper part comprises a first wider end and a first narrower end opposing to the first wider end, and a first width of the first wider end is greater than a second width of the first narrower end; and

a second waveguide disposed on the first waveguide, the second waveguide comprising a second taper part and a second straight part connected to the second taper part, the second taper part being disposed on and optically coupled with the first taper part, wherein the second taper part comprises a second wider end and a second narrower end opposing to the second wider end, and a third width of the second wider end is greater than a fourth width of the second narrower end,

wherein a thickness of the first waveguide is larger than a thickness of the second waveguide, the first straight part connects with the first wider end, and the first straight part and the first wider end are substantially identical in width,

wherein the second straight part connects with the second wider end, and the second straight part and the second wider end are substantially identical in width.

19. The optical system of claim 14, wherein a length of the first straight part is substantially equal to or larger than a length of the first taper part, and a length of the second straight part is substantially equal to or larger than a length of the second taper part.

20. The optical system of claim 18, wherein a length of the first straight part is substantially equal to or larger than a length of the first taper part, and a length of the second straight part is substantially equal to or larger than a length of the second taper part.

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