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ISOLATOR

Abstract

An isolator **10** includes a substrate **11**, waveguide portions **12**, an insulating layer **13**, and a non-reciprocal member **14**. The waveguide portions **12** extend along a main surface of the substrate **11**, and are positioned side by side on the main surface. The insulating layer **13** covers at least part of outer edges of the waveguide portions **12**, and includes a recess **18** overlapping with a first waveguide portion **16** when viewed in a normal direction of the main surface. The non-reciprocal member **14** overlaps with at least part of the first waveguide portion **16** inside the recess **18** when viewed in the normal direction. In a cross-section perpendicular to an extension direction of the first waveguide portion **16**, expressions (1) and (2) are satisfied: w1≤w3≤mfd1+mfd2−w2−2xx . . . (1), x≥(mfd2−w2)/2 . . . (2).

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Background/Summary

TECHNICAL FIELD
[0001] The present invention relates to an isolator.
BACKGROUND OF INVENTION
[0002] A proposed isolator utilizes a non-reciprocal phase effect (see Patent Literature 1). Consideration has been made to formation of the isolator on a semiconductor substrate. The semiconductor substrate also includes other stacked constituent elements, and an insulating film is thus formed to a relatively high position from the substrate. Forming an isolator on a semiconductor substrate needs disposing a magnetic member adjacent to a waveguide that is formed as a core on the substrate. Consideration has been made to forming a trench by etching to complete a semiconductor process, and embedding a magnetic material in the trench thus formed.
CITATION LIST
Patent Literature
[0003] Patent Literature 1: International Publication No. 2007/083419
SUMMARY
Problem to be Solved
[0004] An isolator is required to be reduced in size while exhibiting a non-reciprocal phase effect.
[0005] In view of the problems with the related art as described above, the present disclosure provides an isolator that can be reduced in size while exhibiting a non-reciprocal phase effect.
Solution to Problem
[0006] In order to solve the problems described above, according to a first aspect, an isolator includes a substrate, a plurality of waveguide portions, an insulating layer, and a non-reciprocal member. The plurality of waveguide portions extends along a main surface of the substrate and is positioned side by side on the main surface. The insulating layer covers at least part of outer edges of the plurality of waveguide portions in a cross-section perpendicular to an extension direction of the plurality of waveguides, and includes a recess in a surface on an opposite side from the substrate at a position overlapping with a first waveguide portion that is part of the plurality of waveguide portions when viewed in a normal direction of the main surface. The non-reciprocal member is positioned to overlap with at least part of the first waveguide portion inside the recess when viewed in the normal direction of the main surface. In a cross-section perpendicular to an extension direction of the first waveguide portion, when a length of the first waveguide portion in a width direction perpendicular to the normal direction is w1, an interval in the width direction between an end of the non-reciprocal member and the waveguide portion adjacent to the first waveguide portion is x, a mode field diameter of the first waveguide portion is mfd1, a mode field diameter of the waveguide portion is mfd2, a length in the width direction of the waveguide portion is w2, and a length in the width direction of the non-reciprocal member is w3, expressions (1) and (2) are satisfied.
[00001] $w1 \leq w3 \leq +m\mathrm{fd1} + \mathrm{mfd2} - w2 - 2 \times x \quad (1) \quad x \geq (\mathrm{mfd2} - w2) / 2 \quad (2)$

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0007] FIG. **1** is a sectional view taken along a cross-section perpendicular to an extension direction of a first waveguide portion of an isolator according to an embodiment.

[0008] FIG. **2** is an explanatory view of a configuration of waveguide portions in the isolator illustrated in FIG. **1** when viewed in a normal direction.
[0009] FIG. **3** is an explanatory view of a configuration of waveguide portions in a variation of FIG. **2** when viewed in the normal direction.
[0010] FIG. **4** is a sectional view of a variation of the isolator illustrated in FIG. **1**.
[0011] FIG. **5** is a sectional view of another variation of the isolator illustrated in FIG. **1**.
[0012] FIG. **6** is an explanatory view of a shape of a recess illustrated in FIG. **1** when viewed in the normal direction.
[0013] FIG. **7** is an explanatory view of a shape of a recess in a variation of FIG. **6** when viewed in the normal direction.
[0014] FIG. **8** is a sectional view taken along a cross-section perpendicular to a width direction of an isolator including a recess in another variation of FIG. **6**.
[0015] FIG. **9** is an explanatory conceptual view for sizes in a width direction of some constituent elements in the isolator illustrated in FIG. **1**.

DESCRIPTION OF EMBODIMENTS

[0016] An isolator according to an embodiment of the present disclosure will be described hereinafter with reference to the drawings.
[0017] As illustrated in FIG. **1**, an isolator **10** includes a substrate **11**, a plurality of waveguide portions **12**, an insulating layer **13**, and a non-reciprocal member **14**. The isolator **10** may further include a box layer **15**. The isolator **10** is assumed to be applied to an electromagnetic wave having a wavelength from 1200 nm to 1600 nm. The isolator **10** may be attached to an emitter. The emitter emits an electromagnetic wave having a wavelength selectable from 1200 nm to 1600 nm.
[0018] The substrate **11** has a flat plate shape. The substrate **11** may be made of a conductor such as a metal, a semiconductor such as silicon, glass, a resin, or the like. In the present embodiment, the substrate **11** is made of silicon (Si).
[0019] The box layer **15** may be stacked to cover a substrate surface of the substrate **11**. The box layer **15** may be made of an insulator such as a silicon oxide film.
[0020] The plurality of waveguide portions **12** extends along a main surface of the substrate **11**. The main surface may be the largest surface. The plurality of waveguide portions **12** is positioned side by side along the main surface. The plurality of waveguide portions **12** may be parallel to each other. The plurality of waveguide portions **12** may correspond to part of a single waveguide directly or indirectly continuous as illustrated in FIG. **2**, or part of waveguides independent from one another, in other words, different from one another as illustrated in FIG. **3**.
[0021] As illustrated in FIG. **1**, the plurality of waveguide portions **12** includes a first waveguide portion **16** and a second waveguide portion **17**. The first waveguide portion **16** is positioned to overlap with a recess **18** of the insulating layer **13** to be described later when viewed in a normal direction of the main surface of the substrate **11**. In the present application, a normal direction means the normal direction of the main surface of the substrate **11**. At least part or the entirety in a width direction of the first waveguide portion **16** may overlap with the recess **18**. A width direction corresponds to a direction perpendicular to both an extension direction and the normal direction of the waveguide portion **12**. In the present application, the width direction and the extension direction mean the width direction and the extension direction of the waveguide portion **12**, respectively, unless particularly limited. The second waveguide portion **17** may be positioned away from the recess **18** when viewed in the normal direction. The first waveguide portion **16** and the second waveguide portion **17** will each be called the waveguide portion **12** unless otherwise distinguished from each other in the following description.
[0022] The waveguide portion **12** is covered at least with the insulating layer **13** and the box layer **15**. The waveguide portion **12** may further be covered with the non-reciprocal member **14**. The waveguide portion **12** will also be referred to as a core. The insulating layer **13** and the box layer **15** will also be referred to as cladding. The core and the cladding may each contain a dielectric. The

waveguide portion **12** will also be referred to as a dielectric line. Materials for the core and the cladding are determined such that the core is larger in relative dielectric constant than the cladding. In other words, the materials for the core and the cladding are determined such that the cladding is larger in refractive index than the core. In such a configuration, an electromagnetic wave propagating in the core can be entirely reflected at a boundary with the cladding. This can reduce a loss of the electromagnetic wave propagating in the core.

[0023] The core and the cladding may be larger in relative dielectric constant than air. The core and the cladding being larger in relative dielectric constant than air can suppress leakage of the electromagnetic wave from the isolator **10**. This can reduce a loss caused by radiation of the electromagnetic wave outward from the isolator **10**. The waveguide portion **12** may be made of silicon or the like.

[0024] The insulating layer **13** covers at least part of outer edges of the plurality of waveguide portions **12** in a cross-section perpendicular to the extension direction. The insulating layer **13** may be positioned on a side of the substrate **11** where the waveguide portions **12** are positioned. The insulating layer **13** may be stacked on an opposite side of the box layer **15** from the substrate **11**.

[0025] The insulating layer **13** may cover at least part of at least a side surface of the first waveguide portion **12**. A side surface is parallel to both the extension direction and the normal direction. As illustrated in FIG. **4**, the insulating layer **13** may alternatively cover part of the side surface of the waveguide portion **12**. The insulating layer **13** may further entirely cover a side surface of the second waveguide portion **17**.

[0026] As illustrated in FIG. **5**, the insulating layer **13** may cover a surface of the first waveguide portion **16** on an opposite side from the substrate **11**. Furthermore, as illustrated in FIGS. **1** and **4**, the insulating layer **13** may cover a surface of the second waveguide portion **17** on an opposite side from the substrate **11**.

[0027] As illustrated in FIGS. **1**, **4**, and **5**, the insulating layer **13** may include the recess **18** positioned to overlap with the first waveguide portion **16**, which is part of the plurality of waveguide portions **12**, when viewed in the normal direction. The recess **18** is recessed in a surface of the insulating layer **13** on an opposite side from the substrate **11**.

[0028] As illustrated in FIG. **1**, the recess **18** may include a bottom surface positioned at the same level in the normal direction as the surface (hereinafter, also called “upper surface”) of the first waveguide portion **16** on the opposite side from the substrate **11**. In other words, the bottom surface of the recess **18** is flush with the upper surface of the first waveguide portion **16**. As illustrated in FIG. **4**, the bottom surface of the recess **18** may alternatively be positioned closer in the normal direction to the substrate **11** than is the upper surface of the first waveguide portion. As illustrated in FIG. **5**, the bottom surface of the recess **18** may still alternatively be farther in the normal direction from the substrate **11** than is the upper surface of the first waveguide portion **16**.

[0029] As illustrated in FIG. **4**, when the bottom surface of the recess **18** is positioned closer in the normal direction to the substrate **11** than is the upper surface of the first waveguide portion **16**, the bottom surface of the recess **18** and the upper surface of the first waveguide portion **16** may have a level difference equal to or less than 100 nm. This is because the level difference may influence crystallization of the non-reciprocal member **14**. When Ce:YIG (cerium-substituted yttrium iron garnet) is used as the non-reciprocal member **14**, a discontinuity in the Ce:YIG film due to the level difference may inhibit crystallization of Ce:YIG during annealing for crystallization. The level difference is thus preferably equal to or less than 100 nm in order to suppress inhibition of crystallization.

[0030] As illustrated in FIG. **6**, the recess **18** is defined by surfaces including first surfaces s**1** that are positioned at end portions in the extension direction of the first waveguide portion **16** and that may be perpendicular to the extension direction. As illustrated in FIG. **7**, the first surfaces s**1** may alternatively be inclined about a straight line parallel to the normal direction from a plane perpendicular to the extension direction. As illustrated in FIG. **8**, the first surfaces s**1** may still

alternatively be inclined outward from the recess **18** with respect to the normal direction.
[0031] The recess **18** may have a length in the width direction equal to or more than a length of the non-reciprocal member **14**, described later, positioned inside the recess **18**. The length in the width direction of the recess **18** may be the minimum length when the length is varied in the normal direction as illustrated in FIG. **8**. The length in the width direction of the recess **18** may be longer than a size of a crystal obtained by crystallization of the non-reciprocal member **14** positioned inside the recess **18**. In other words, the length in the width direction of the recess **18** may be longer than the crystal size of the non-reciprocal member **14** positioned inside the recess **18**.
[0032] The non-reciprocal member **14** shifts a phase of an electromagnetic wave in a TM mode propagating in the first waveguide portion **16**. A magnetic field for development of non-reciprocity by the non-reciprocal member **14** may be applied to the isolator **10**.
[0033] As illustrated in FIGS. **1**, **4**, **5**, and **8**, the non-reciprocal member **14** may be positioned to overlap with at least part of the first waveguide portion **16** at least inside the recess **18** when viewed in the normal direction. The non-reciprocal member **14** may further be positioned to cover a region other than the recess **18** of the insulating layer **13** when viewed in the normal direction.
[0034] The non-reciprocal member **14** may be positioned in contact with at least part of the bottom surface of the recess **18**. For example, the non-reciprocal member **14** may be positioned in contact with part of the bottom surface of the recess **18**. As illustrated in FIGS. **1**, **4**, and **5**, the non-reciprocal member **14** may alternatively be positioned in contact with the entire bottom surface of the recess **18**.
[0035] As illustrated in FIGS. **1** and **4**, the non-reciprocal member **14** may be in contact with at least part of the first waveguide portion **16**. For example, as illustrated in FIGS. **1** and **4**, the non-reciprocal member **14** may be in contact with the entire upper surface of the first waveguide portion **16**. Furthermore, as illustrated in FIG. **4**, the non-reciprocal member **14** may be in contact with parts, adjacent to the upper surface, of both end surfaces in the width direction, in other words, side surfaces, of the first waveguide portion **16**.
[0036] As illustrated in FIG. **5**, the non-reciprocal member **14** is not necessarily in contact with the first waveguide portion **16**. Specifically, the insulating layer **13** may be interposed between the non-reciprocal member **14** and the first waveguide portion **16**. The insulating layer **13** interposed between the first waveguide portion **16** and the non-reciprocal member **14** may have a thickness in the normal direction equal to or less than a first value. The first value may be determined in accordance with a mode field diameter of the first waveguide portion **16** and the thickness in the normal direction of the first waveguide portion **16**. More specifically, the first value may be obtained by subtracting a half of the thickness in the normal direction of the first waveguide portion **16** from the mode field diameter of the first waveguide portion **16**.
[0037] In the present embodiment, the waveguide portion **12** has a rectangular sectional shape. The mode field diameter is defined in such a configuration. The electromagnetic wave in the TM mode propagating in the waveguide portion **12** includes an electric field component having energy that decreases outside the waveguide portion **12** in a direction away from the waveguide **12**. The energy of the electric field component of the electromagnetic wave in the TM mode outside the waveguide portion **12** has a magnitude according to a Gaussian distribution. The mode field diameter is defined as a distance to a position where the magnitude of the energy decreases to 1/e.sup.2 of the magnitude of the energy of the electric field component at a center of a cross-section perpendicular to the extension direction of the waveguide portion **12**.
[0038] In the present disclosure, the mode field diameter may be measured in the following manner. When light enters one of the end surfaces of the first waveguide portion **16** and outgoing light from the other end surface is captured with a camera, a light intensity distribution on the end surface is detected. In this light intensity distribution, the mode field diameter is measured as an interval between a peak position and a position at an intensity of 1/e.sup.2 of the peak intensity.
[0039] The mode field diameter at the waveguide portion **12** is determined in accordance with a

length in the width direction of the waveguide portion **12** in the cross-section perpendicular to the extension direction of the waveguide portion **12**, a length in the normal direction of the waveguide portion **12**, a refractive index of the waveguide portion **12**, a refractive index of the insulating layer **13**, and a wavelength of the electromagnetic wave propagating in the waveguide portion **12**. The wavelength of the electromagnetic wave propagating in the waveguide portion **12** may be determined by the emitter attached to the isolator **10**.

[0040] For example, the mode field diameter is 800 nm when the length in the width direction of the waveguide portion **12** is 400 nm, the length in the normal direction of the waveguide portion **12** is 220 nm, the refractive index of the waveguide portion **12** is 3.45, the refractive index of the insulating layer **13** is 1.53, and the wavelength of the electromagnetic wave in the TM mode propagating in the waveguide portion **12** is 1550 nm.

[0041] Alternatively, for example, the mode field diameter is 520 nm when the length in the width direction of the waveguide portion **12** is 500 nm, the length in the normal direction of the waveguide portion **12** is 220 nm, the refractive index of the waveguide portion **12** is 3.45, the refractive index of the insulating layer **13** is 1.53, and the wavelength of the electromagnetic wave in the TM mode propagating in the waveguide portion **12** is 1550 nm.

[0042] As illustrated in FIG. **9**, in a cross-section perpendicular to the extension direction of the first waveguide portion **16**, a length w3 in the width direction of the non-reciprocal member **14** satisfies expression (1) below.

[00002] $w1 \leq w3 \leq +m\mathrm{fd1} + \mathrm{mfd2} - w2 - 2 \times x \quad (1)$

[0043] In Expression (1), w1 is a length in the width direction of the first waveguide portion **16**. w2 is a length in the width direction of the second waveguide portion **17** adjacent to the first waveguide portion **16**. When the second waveguide portion **17** is disposed adjacent to each side in the width direction of the first waveguide portion **16**, w2 may be the length in the width direction of the second waveguide portion **17** positioned closer to the first waveguide portion **16**. x is an interval in the width direction between an end in the width direction of the non-reciprocal member **14** and the second waveguide portion **17** adjacent to the first waveguide portion **16**. When the second waveguide portion **17** is disposed adjacent to each side in the width direction of the first waveguide portion **16**, x may be the interval from the second waveguide portion **17** positioned closer to the first waveguide portion **16**. mfd1 is the mode field diameter of the first waveguide portion **16**. mfd2 is the mode field diameter of the second waveguide portion **17** adjacent to the first waveguide portion **16**. When the second waveguide portion **17** is disposed adjacent to each side in the width direction of the first waveguide portion **16**, mfd2 may be the mode field diameter of the second waveguide portion **17** positioned closer to the first waveguide portion **16**.

[0044] The interval x in the width direction between the end in the width direction of the non-reciprocal member **14** and the second waveguide portion **17** adjacent to the first waveguide portion **16** further satisfies expression (2) below.

[00003] $x \geq (\mathrm{mfd2} - w2) / 2 \quad (2)$

[0045] The non-reciprocal member **14** may be made of YIG (yttrium iron garnet). The non-reciprocal member **14** may thus contain YIG. YIG as a material for the non-reciprocal member **14** may be partially substituted YIG, such as Ce:YIG or Bi:YIG (bismuth-substituted YIG). Examples of the material for the non-reciprocal member **14** may include a ferromagnetic material such as FeCo, FeNi, or CoPt, and a substance containing the ferromagnetic material. Examples of the material for the non-reciprocal member **14** may further include a dielectric composited with magnetic nanoparticles, such as a nanogranular material. The material for the non-reciprocal member **14** is not limited to the above, and examples thereof may further include other various magnetic materials.

[0046] In the present embodiment, the isolator **10** thus configured includes the substrate **11**, the plurality of waveguide portions **12**, the insulating layer **13**, and the non-reciprocal member **14**. The plurality of waveguide portions extends along the main surface of the substrate **11** and is positioned side by side on the main surface. The insulating layer covers at least part of the outer edges of the plurality of waveguide portions **12** in the cross-section perpendicular to the extension direction of the plurality of waveguides **12**, and includes the recess **18** in the surface on the opposite side from the substrate **11** at the position overlapping with the first waveguide portion **16** that is part of the plurality of waveguide portions **12** when viewed in the normal direction of the main surface. The non-reciprocal member is positioned to overlap with at least part of the first waveguide portion **16** inside the recess **18** when viewed in the normal direction of the main surface. In the cross-section perpendicular to the extension direction of the first waveguide portion **16**, when the length of the first waveguide portion **16** in the width direction perpendicular to the normal direction is w1, the interval in the width direction between the end of the non-reciprocal member **14** and the waveguide portion **17** adjacent to the first waveguide portion **16** is x, the mode field diameter of the first waveguide portion **16** is mfd1, the mode field diameter of the waveguide portion **17** is mfd2, the length in the width direction of the waveguide portion **17** is w2, and the length in the width direction of the non-reciprocal member **14** is w3, expressions (1) and (2) are satisfied. To reduce a size of an isolator, waveguides may be disposed partially adjacent to each other. However, waveguides having a small interval may function as a directional coupler and an electromagnetic wave may propagate from a waveguide to another waveguide. Furthermore, if a waveguide undesired to develop non-reciprocity is positioned close to a waveguide desired to develop non-reciprocity, the waveguide undesired to develop non-reciprocity may also develop non-reciprocity. Regarding such a phenomenon, the isolator **10** configured as described above satisfies expression (2) and can thus suppress development of non-reciprocity for the second waveguide portion **17**. Furthermore, the isolator **10** satisfies expression (1) and can thus prevent the waveguide portion **16** of the first waveguide portion **16** and the second waveguide portion **17** from functioning as a directional coupler while exhibiting an enhanced non-reciprocity development effect. The isolator **10** can thus develop desired non-reciprocity and suppress influence on the other waveguide portions **12** while having a smaller interval between the first waveguide portion **16** and the second waveguide portion **17**. The isolator **10** can therefore be reduced in size while exhibiting a desired non-reciprocity effect.

[0047] In the isolator **10**, at least part of the first waveguide portion **16** is in contact with the non-reciprocal member **14**. The isolator **10** thus configured minimizes the interval between the first waveguide portion **16** and the non-reciprocal member **14** and can therefore enhance non-reciprocity developed by the first waveguide portion **16**.

[0048] In the isolator **10**, the insulating layer **13** is interposed between the first waveguide portion **16** and the non-reciprocal member **14**. In the isolator **10** thus configured, the insulating layer **13** protects the first waveguide portion **16** in a subprocess of forming a non-reciprocal member in a manufacture process, and can therefore reduce a loss of the electromagnetic wave in the first waveguide portion **16** in a completed product.

[0049] In the isolator **10**, the thickness in the normal direction of the insulating layer **13** interposed between the first waveguide portion **16** and the non-reciprocal member **14** is equal to or less than a value determined in accordance with the mode field diameter of the first waveguide portion **16** and the thickness in the normal direction of the first waveguide portion **16**. The isolator **10** thus configured can cause the first waveguide portion **16** to develop non-reciprocity even when the insulating layer **13** is interposed between the first waveguide portion **16** and the non-reciprocal member **17**.

[0050] In the isolator **10**, the length in the width direction of the recess **18** is larger than the crystal size of the non-reciprocal member **14**. The isolator **10** thus configured can promote crystallization of the non-reciprocal member **14** and can therefore cause non-reciprocal member **14** to develop sufficient non-reciprocity.

[0051] Among the surfaces defining the recess **18** of the isolator **10**, the surfaces s**1** positioned at the end portions in the extension direction are inclined from a plane perpendicular to the extension direction. The isolator **10** thus configured gently changes an effective refractive index of the first waveguide portion **16** from a range overlapping with the recess **18** toward outside a range of the recess **18**. The isolator **10** gently changes the effective refractive index of the first waveguide portion **16** to suppress reflection of the electromagnetic wave at a boundary between the range overlapping with the recess **18** and outside the range of the recess **18** in the first waveguide portion **16**. As a result, the isolator **10** reduces a loss of the electromagnetic wave.

[0052] Among the surfaces defining the recess **18** of the isolator **10**, the surfaces s**1** positioned at the end portions in the extension direction are inclined outward from the recess **18** with respect to the normal direction. The isolator **10** thus configured gradually increases the distance from the upper surface of the first waveguide portion **16** to the non-reciprocal member **14**, and therefore gently changes the effective refractive index of the first waveguide portion **16** from the range overlapping with the recess **18** toward outside the range of the recess **18**. As a result, the isolator **10** reduces a loss of the electromagnetic wave.

[0053] The embodiment of the present disclosure has been described with reference to the figures and implementation examples. Note that those skilled in the art can easily apply various changes or modifications in accordance with the present disclosure. Accordingly, note that these changes or modifications are included in the scope of the present disclosure. For example, functions and the like included in individual constituent units or individual steps can be reallocated without logical inconsistency. A plurality of constituent units or steps can be combined into a single constituent unit or step, or each constituent unit or step can be divided into a plurality of units or steps.

[0054] In the present disclosure, expressions such as “first” and “second” are identifiers for distinction between relevant configurations. In the present disclosure, the configurations distinguished by the expressions such as “first” and “second” can have their numbers exchanged. For example, the first waveguide portion and the second waveguide portion can have their identifiers “first” and “second” exchanged. The identifiers are exchanged simultaneously. These configurations are still distinguished after the exchange of the identifiers. The identifiers may be deleted. The configurations having their identifiers deleted are distinguished by reference signs. In the present disclosure, the recitation of the identifiers such as “first” and “second” should not solely be used as grounds for interpretation of the order of these configurations or the presence of any identifier having a smaller number.

REFERENCE SIGNS

[0055] **10** isolator [0056] **11** substrate [0057] **12** waveguide portion [0058] **13** insulating layer [0059] **14** non-reciprocal member [0060] **15** box layer [0061] **16** first waveguide portion [0062] **17** second waveguide portion [0063] **18** recess [0064] s**1** first surface

Claims

1. An isolator comprising: a substrate; a plurality of waveguide portions extending along a main surface of the substrate and positioned side by side on the main surface; an insulating layer covering at least part of outer edges of the plurality of waveguide portions in a cross-section perpendicular to an extension direction of the plurality of waveguides, and including a recess in a surface on an opposite side from the substrate at a position overlapping with a first waveguide portion that is part of the plurality of waveguide portions when viewed in a normal direction of the main surface; and a non-reciprocal member positioned to overlap with at least part of the first waveguide portion inside the recess when viewed in the normal direction of the main surface, wherein in a cross-section perpendicular to an extension direction of the first waveguide portion, when a length of the first waveguide portion in a width direction perpendicular to the normal direction is w1, an interval in the width direction between an end of the non-reciprocal member and the waveguide portion adjacent to the first waveguide portion is x, a mode field diameter of the first waveguide portion is mfd1, a mode field diameter of the waveguide portion is mfd2, a length in the width direction of the waveguide portion is w2, and a length in the width direction of the non-reciprocal member is w3, expressions (1) and (2) are satisfied:

$w1 \leq w3 \leq +m\mathrm{fd1} + \mathrm{mfd2} - w2 - 2 \times x$ (1) $x \geq (\mathrm{mfd2} - w2) / 2.$ (2)

2. The isolator according to claim 1, wherein at least part of the first waveguide portion is in contact with the non-reciprocal member.

3. The isolator according to claim 1, wherein the recess includes a bottom surface positioned closer to the substrate in the normal direction than is a position of a surface of the first waveguide portion on an opposite side from the substrate.

4. The isolator according to claim 1, wherein the insulating layer is interposed between the first waveguide portion and the non-reciprocal member.

5. The isolator according to claim 4, wherein a thickness in the normal direction of the insulating layer interposed between the first waveguide portion and the non-reciprocal member is equal to or less than a value determined in accordance with the mode field diameter of the first waveguide portion and a thickness in the normal direction of the first waveguide portion.

6. The isolator according to claim 1, wherein the recess has a length in the width direction larger than a crystal size of the non-reciprocal member.

7. The isolator according to claim 1, wherein the non-reciprocal member contains YIG (yttrium iron garnet).

8. The isolator according to claim 1, wherein the recess is defined by surfaces including a surface that is positioned at an end portion in the extension direction and that is inclined from a plane perpendicular to the extension direction.

9. The isolator according to claim 1, wherein the recess is defined by surfaces including a surface that is positioned at an end portion in the extension direction and that is inclined outward from the recess with respect to the normal direction.