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(54) **OPTICAL DEVICE AND METHOD FOR MANUFACUTURING THE OPTICAL DEVICE**

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USPC **385/14**; 156/278; 216/24

(57) **ABSTRACT**

The invention provides an optical device and an optical device manufacturing method wherein provisions are made to be able to precisely align an optical fiber relative to a substrate without heating the substrate and to maintain the optimum alignment condition for an extended period of time. More specifically, the invention provides an optical device manufacturing method which includes the steps of forming a first metallic film on a portion of a substrate, forming a second metallic film on a portion of the outer circumference of an optical fiber, and bonding together the first metallic film and the second metallic film by surface activated bonding, and an optical device manufactured by such a manufacturing method.

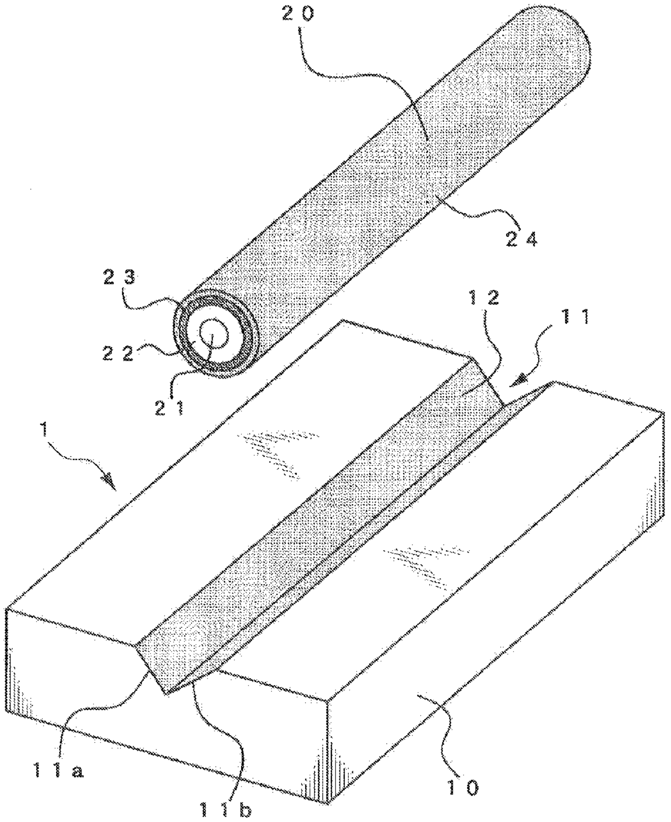


FIG.1

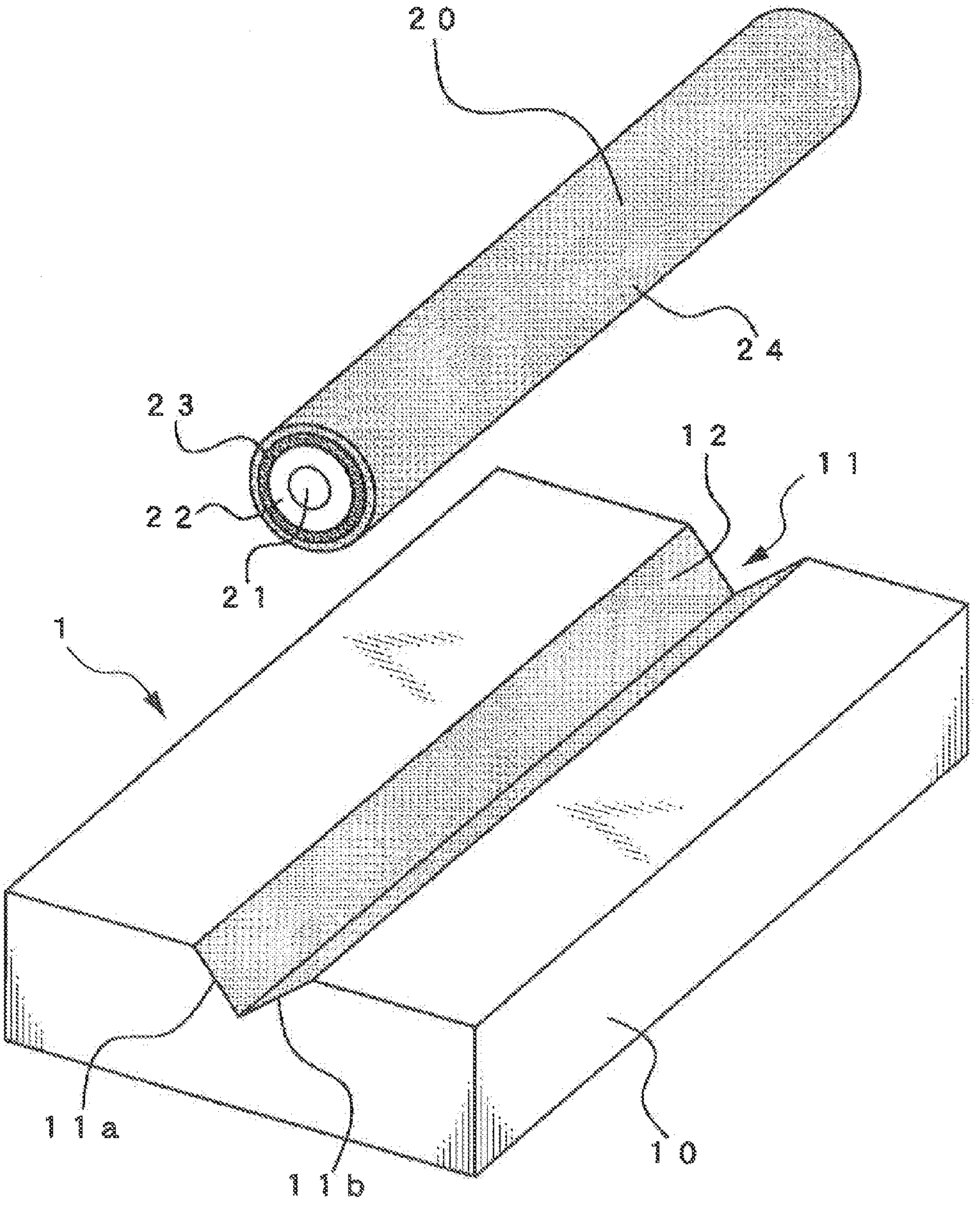


FIG.2

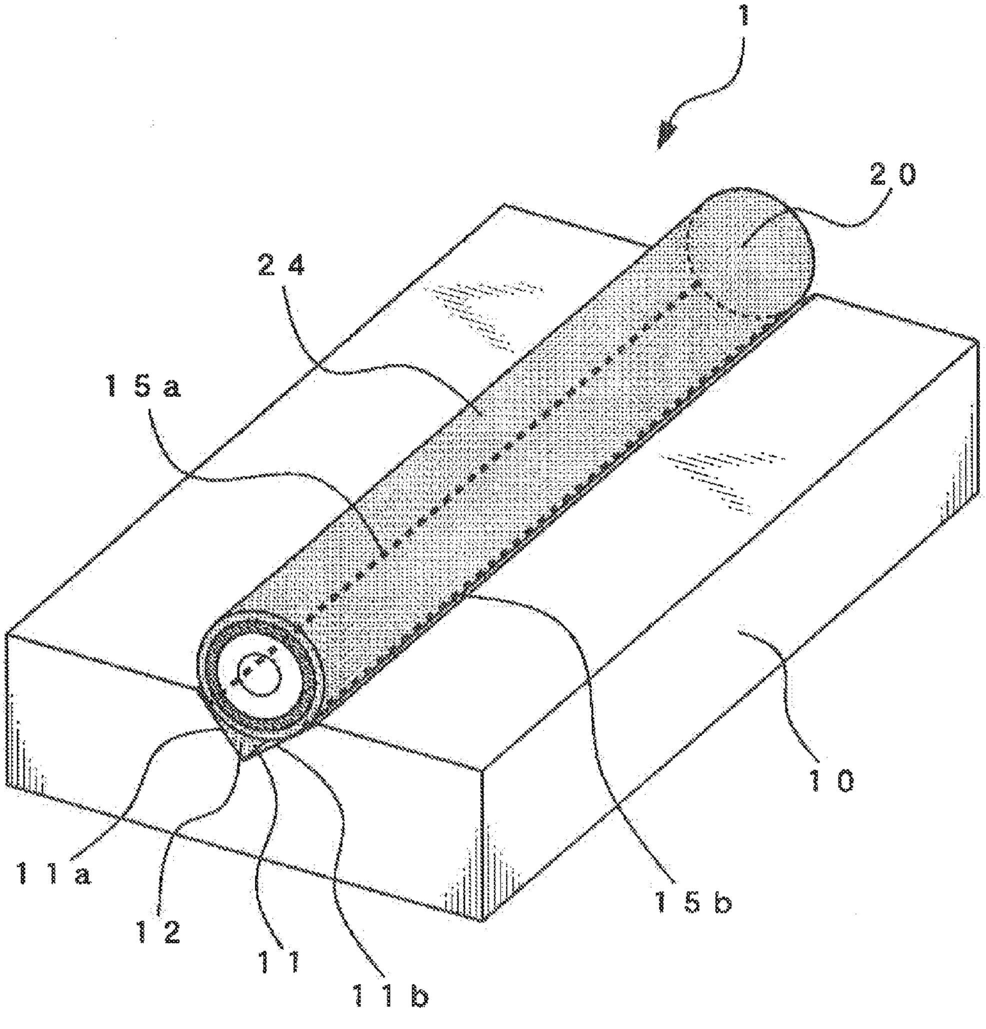


FIG.3(a)

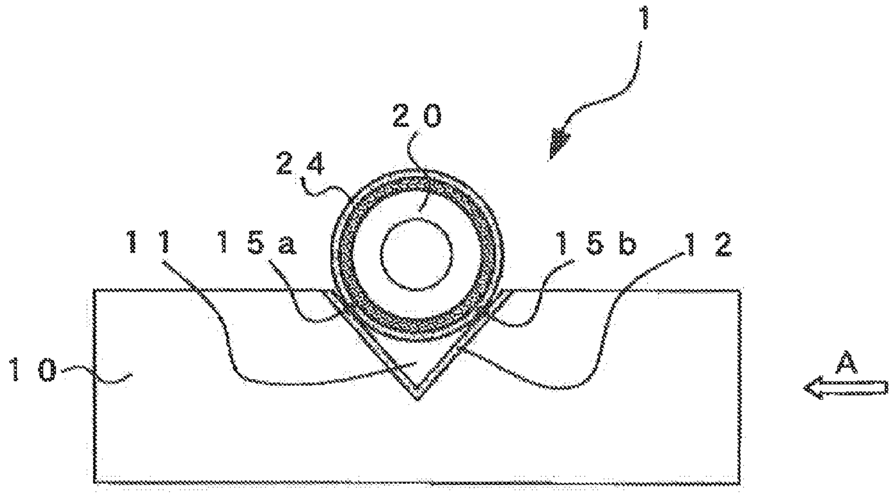


FIG.3(b)

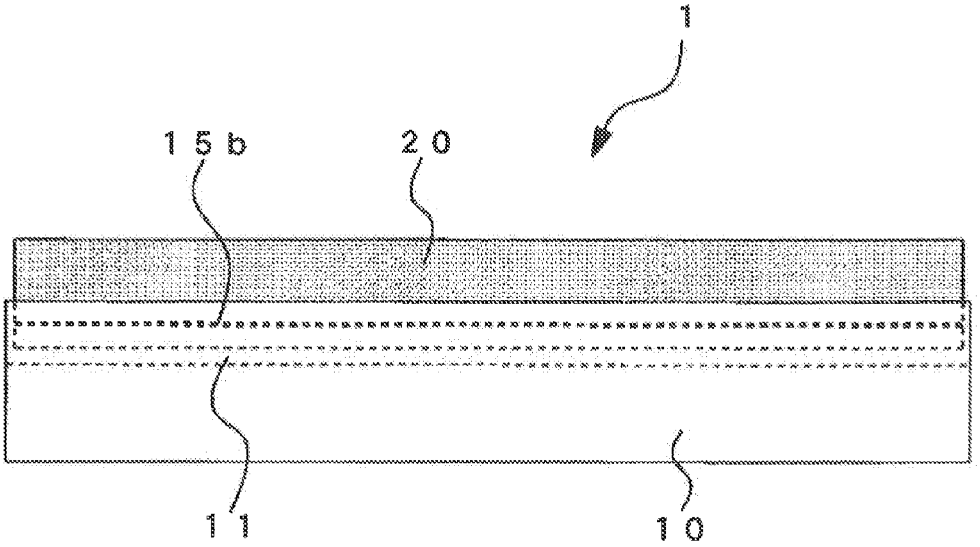


FIG.4

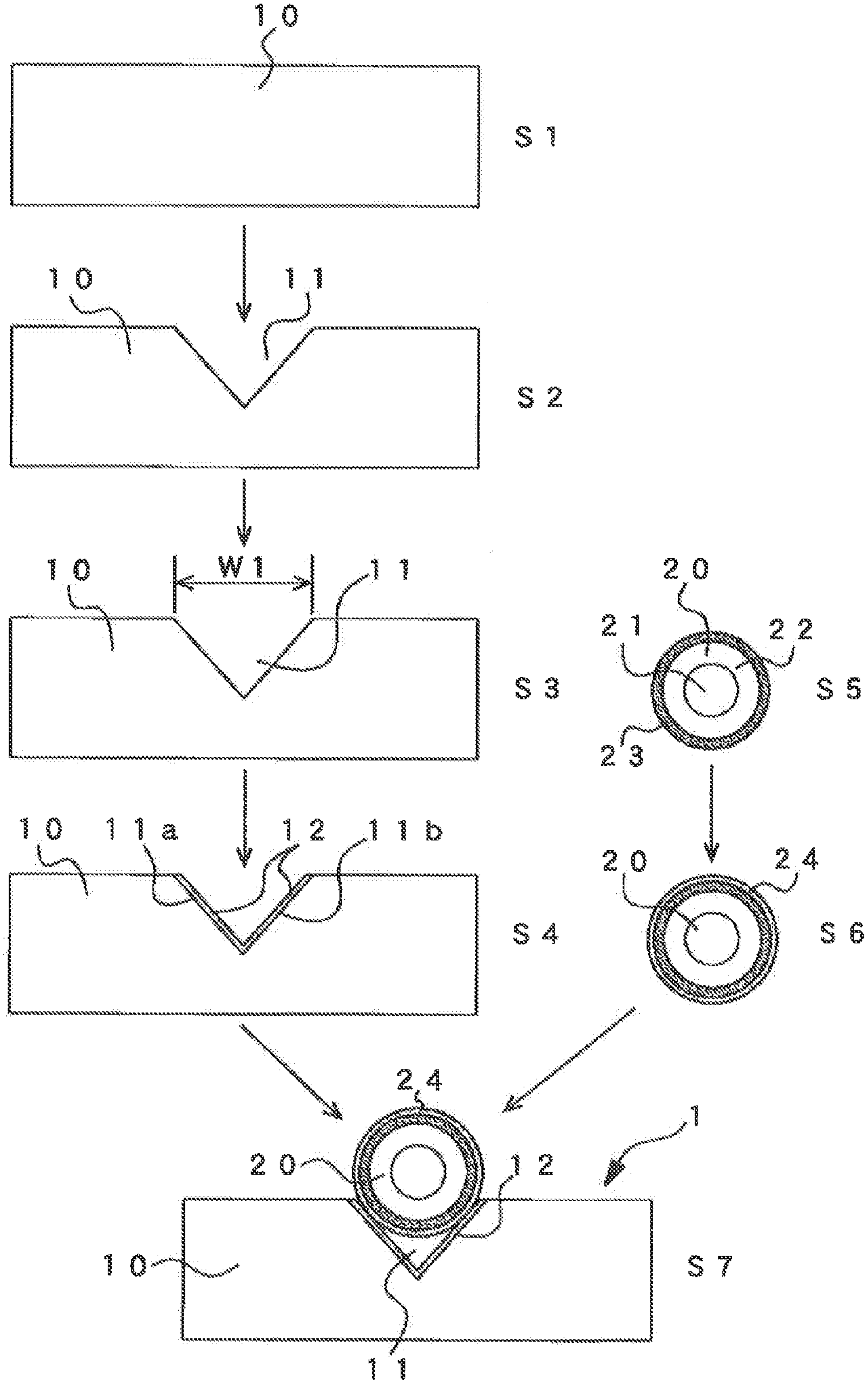

10
S1
10
11
S2
10
W1
11
S3
20
21
22
23
S5
10
11a
12
11b
S4
20
24
20
S6
24
20
12
1
10
S7
11

FIG.5

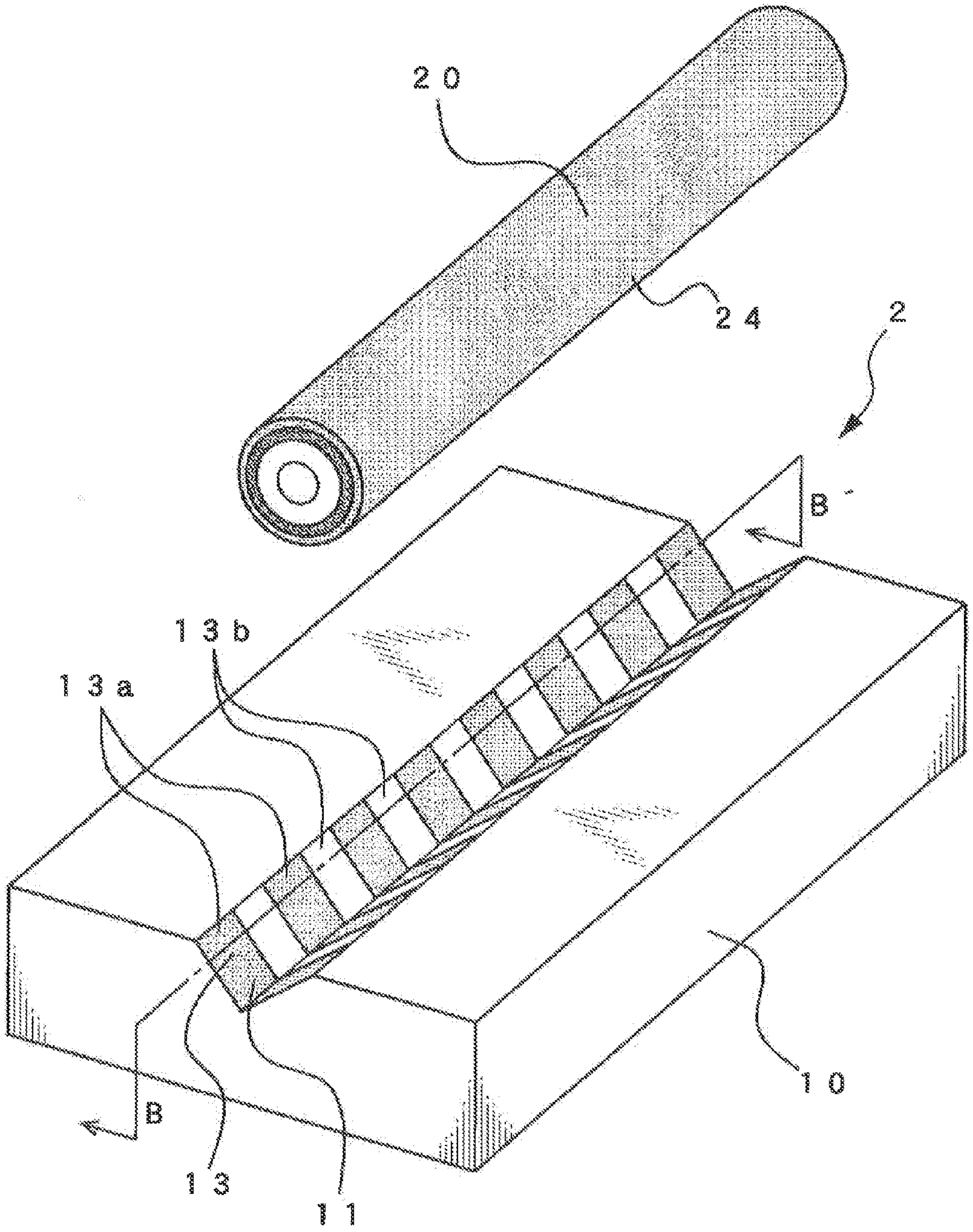


FIG.6(a)

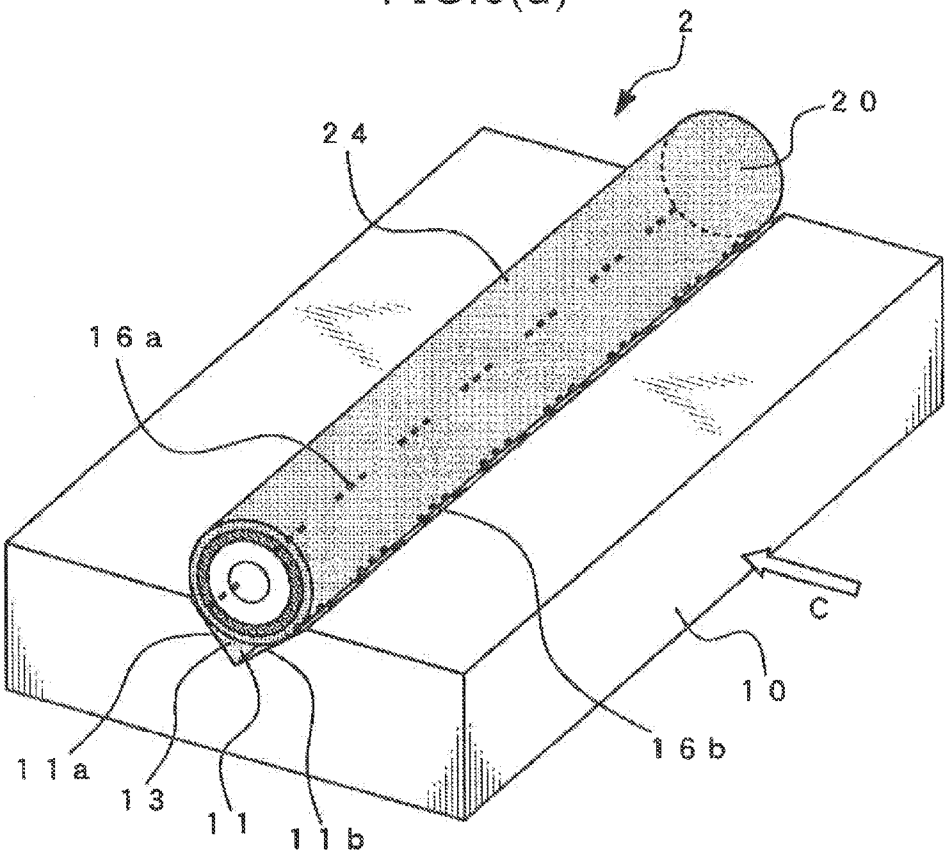


FIG.6(b)

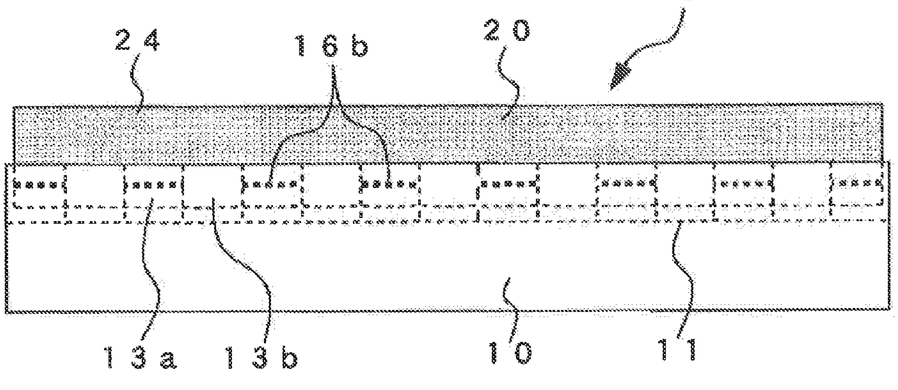


FIG.7

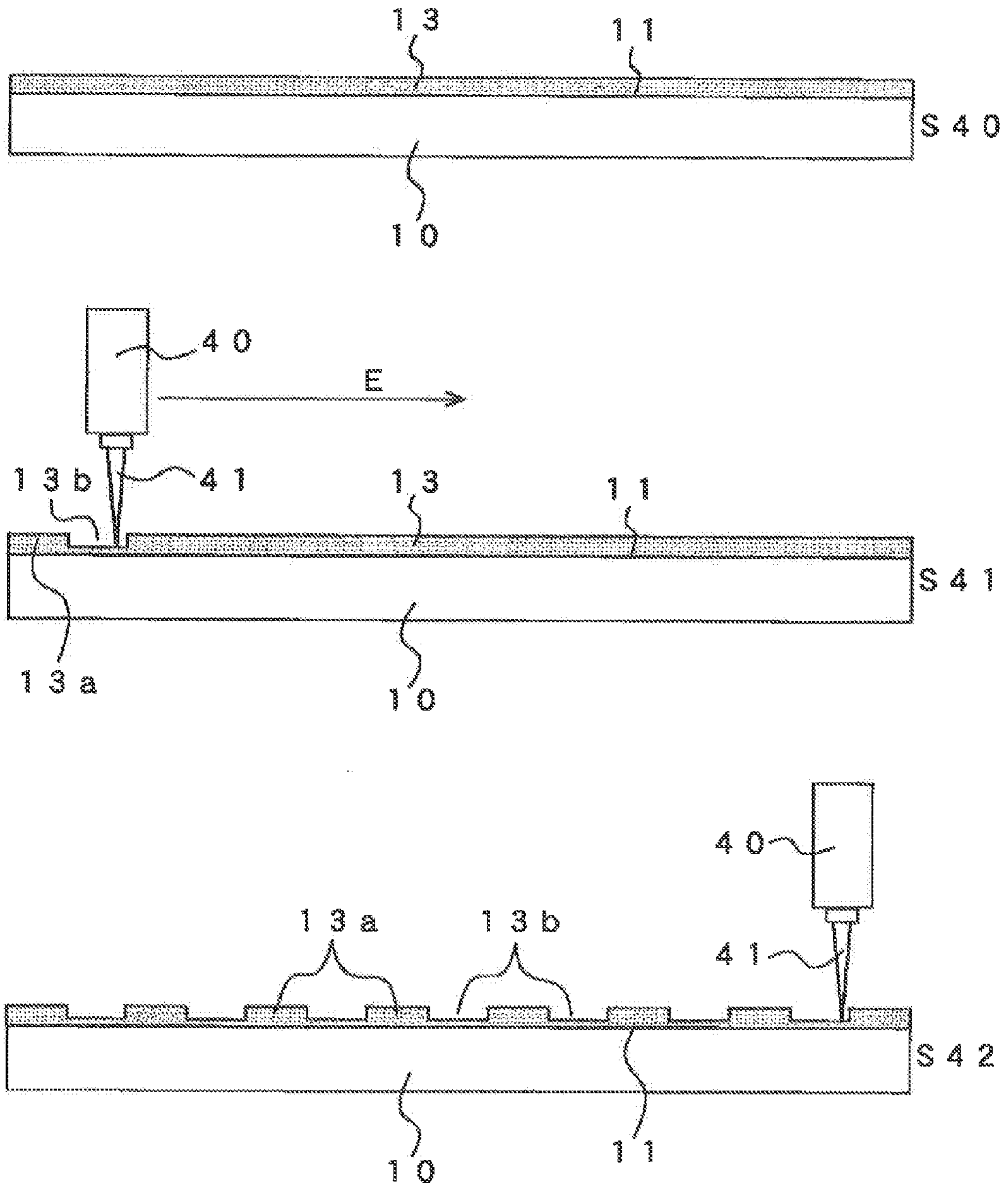


FIG.8

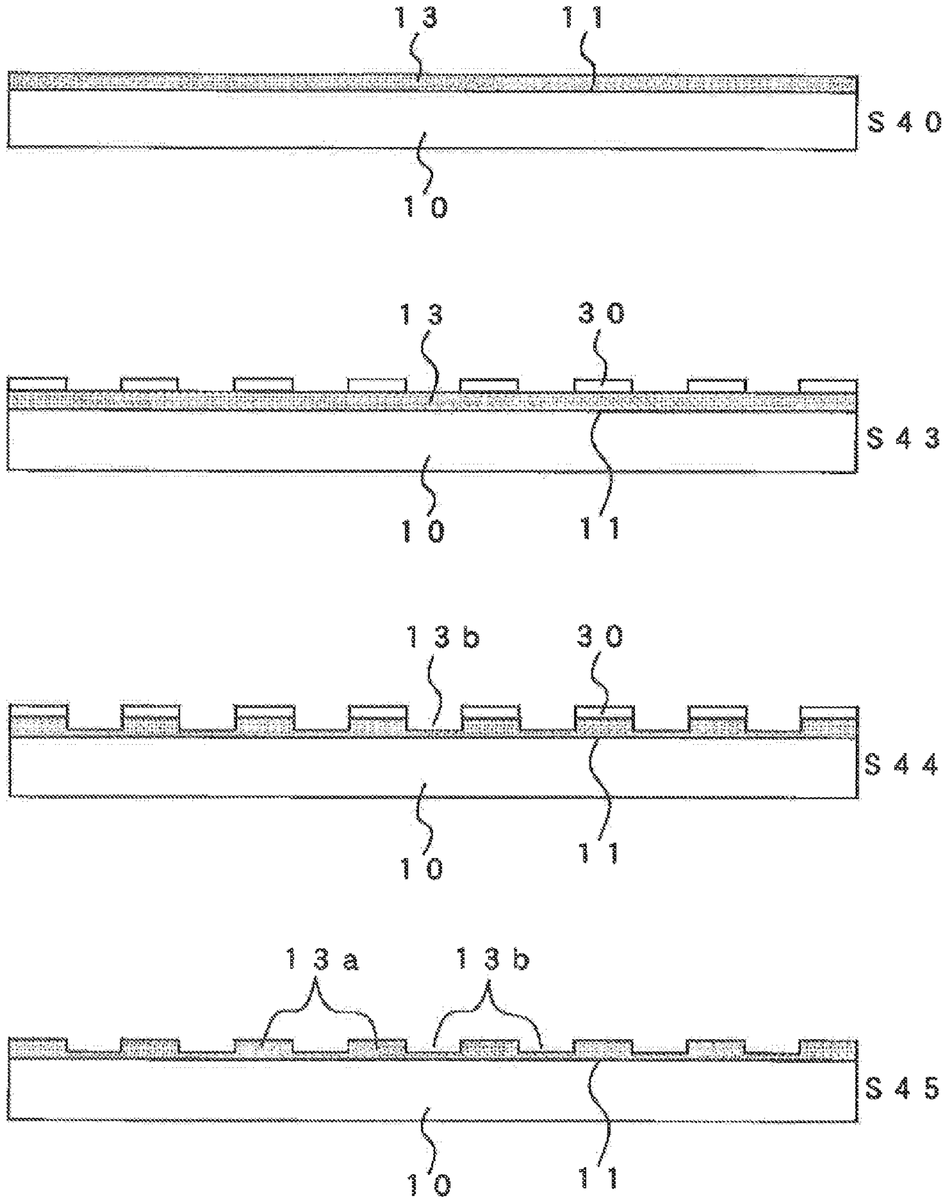


FIG.9(a)

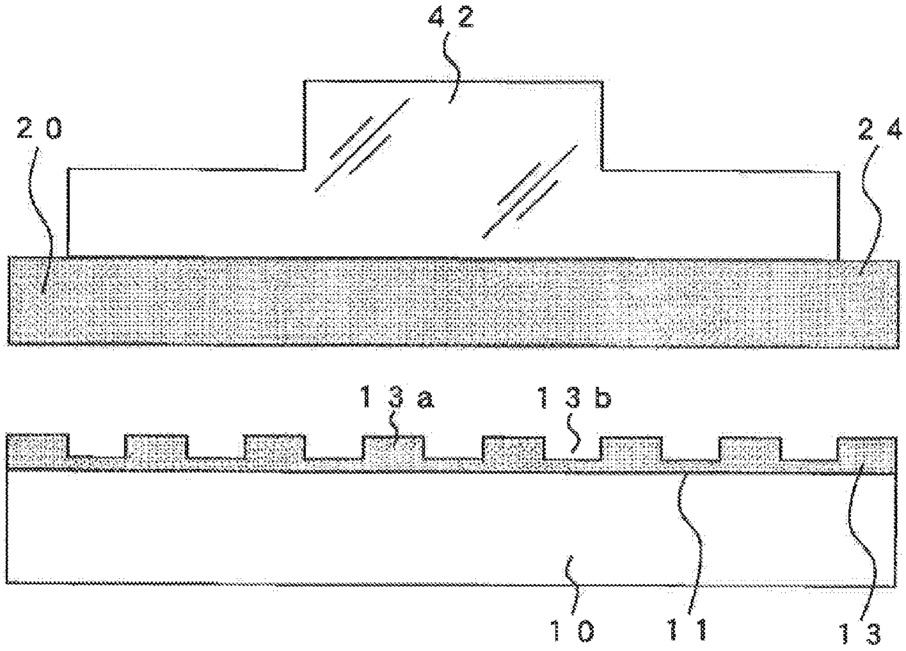


FIG.9(b)

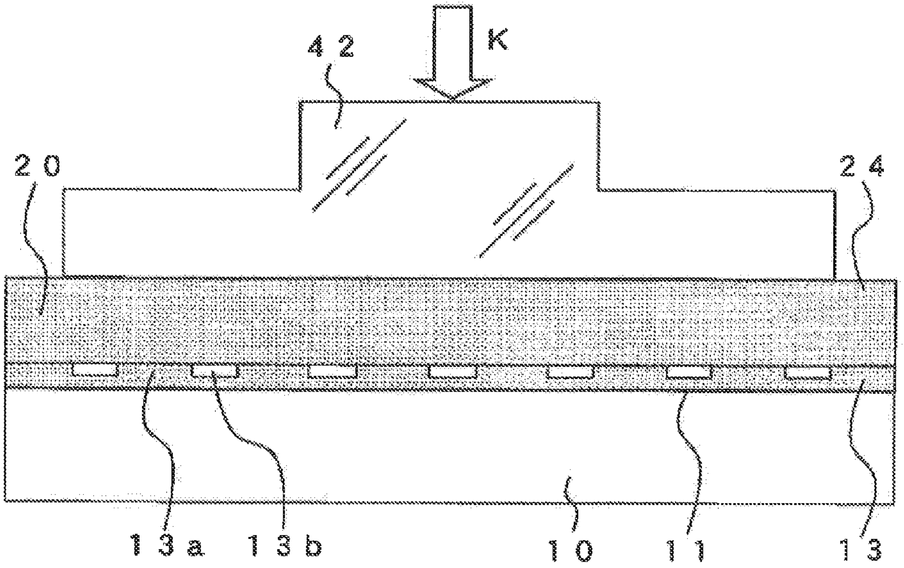


FIG.10(a)

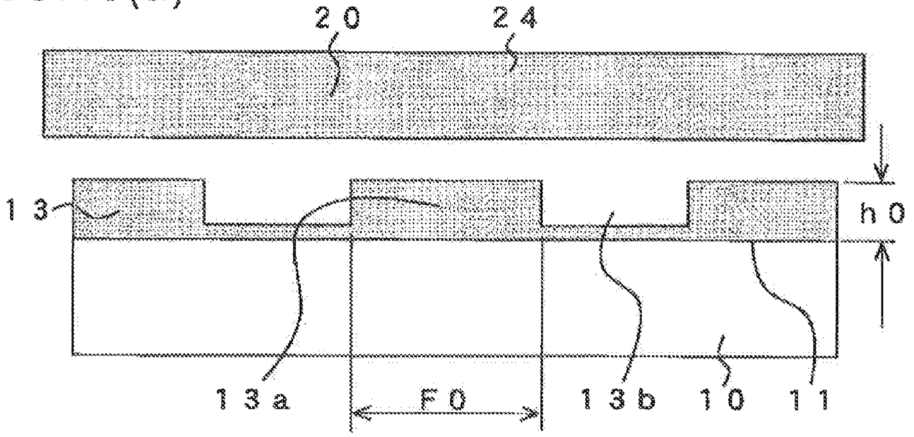


FIG.10(b)

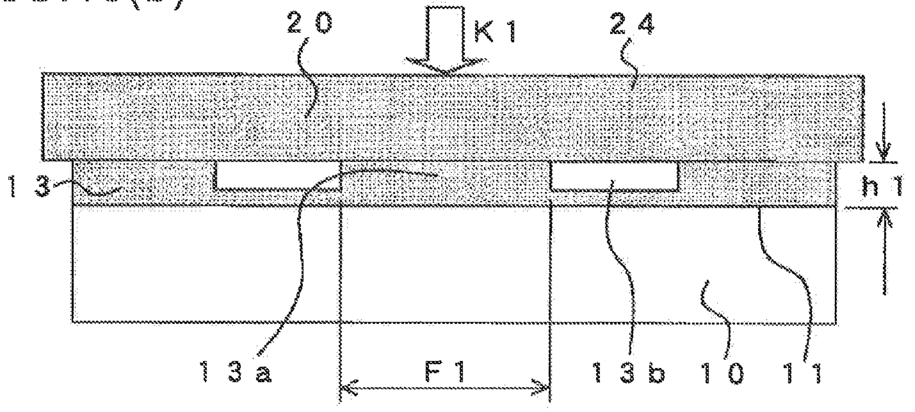


FIG.10(c)

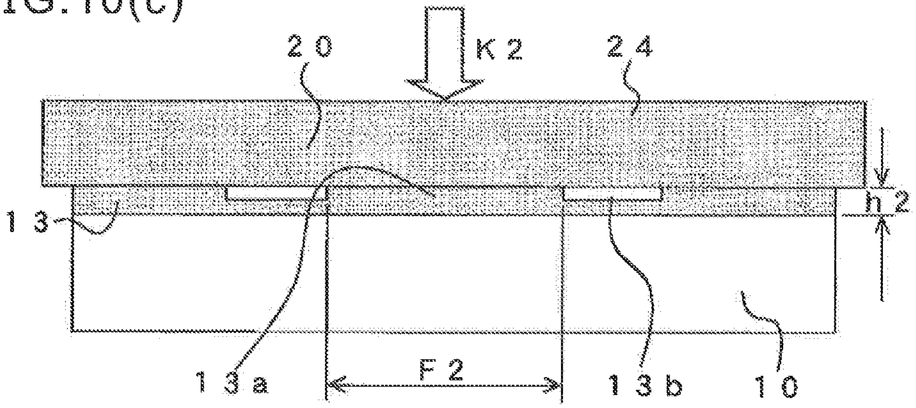


FIG.11(a)

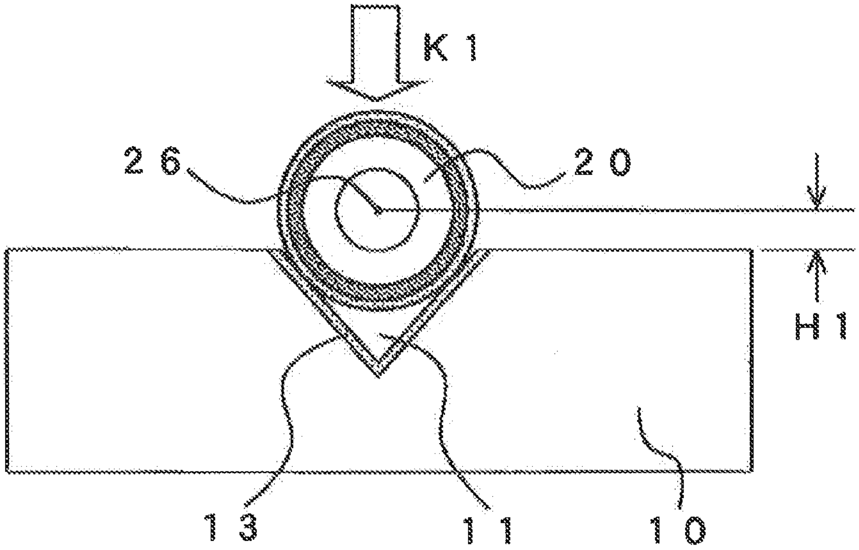


FIG.11(b)

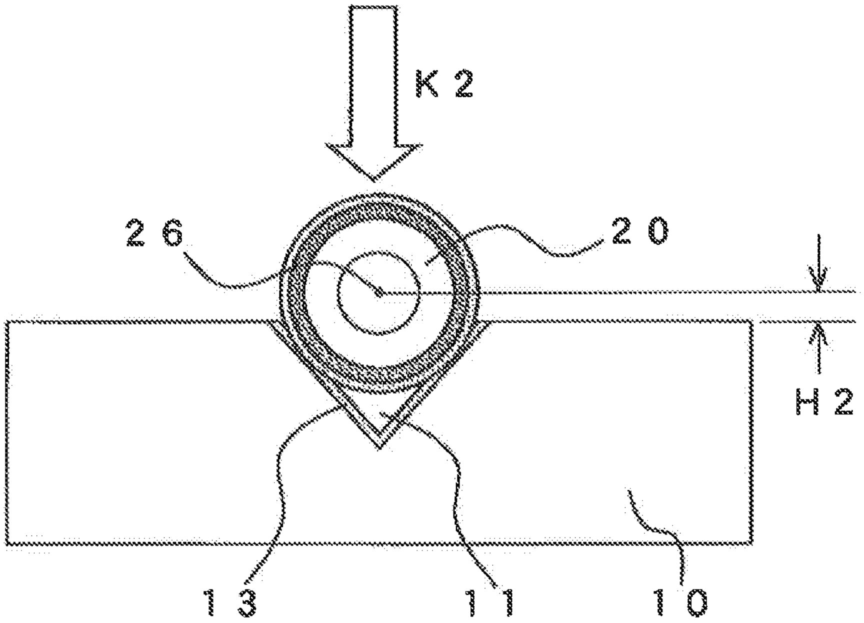


FIG.12

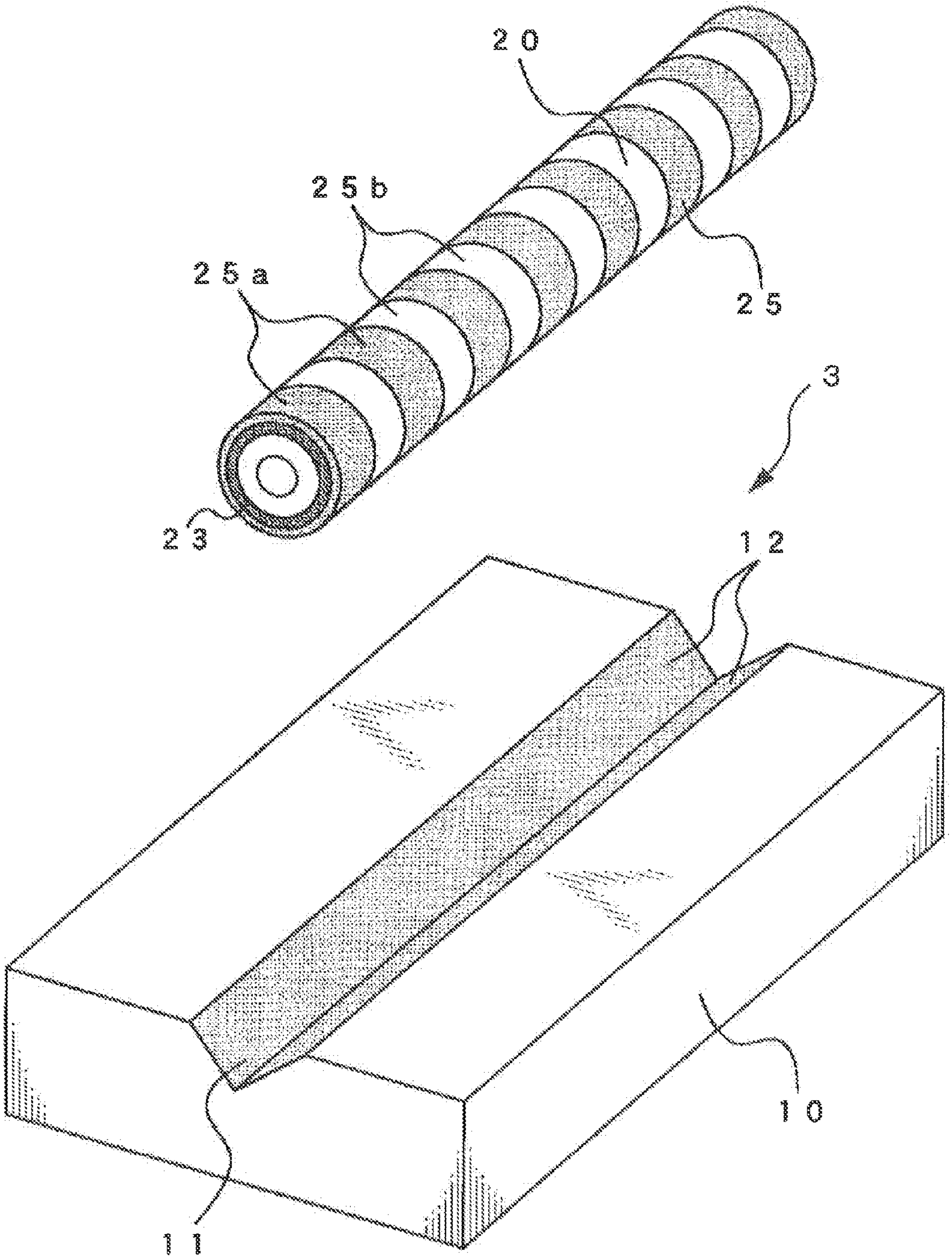


FIG.13(a)

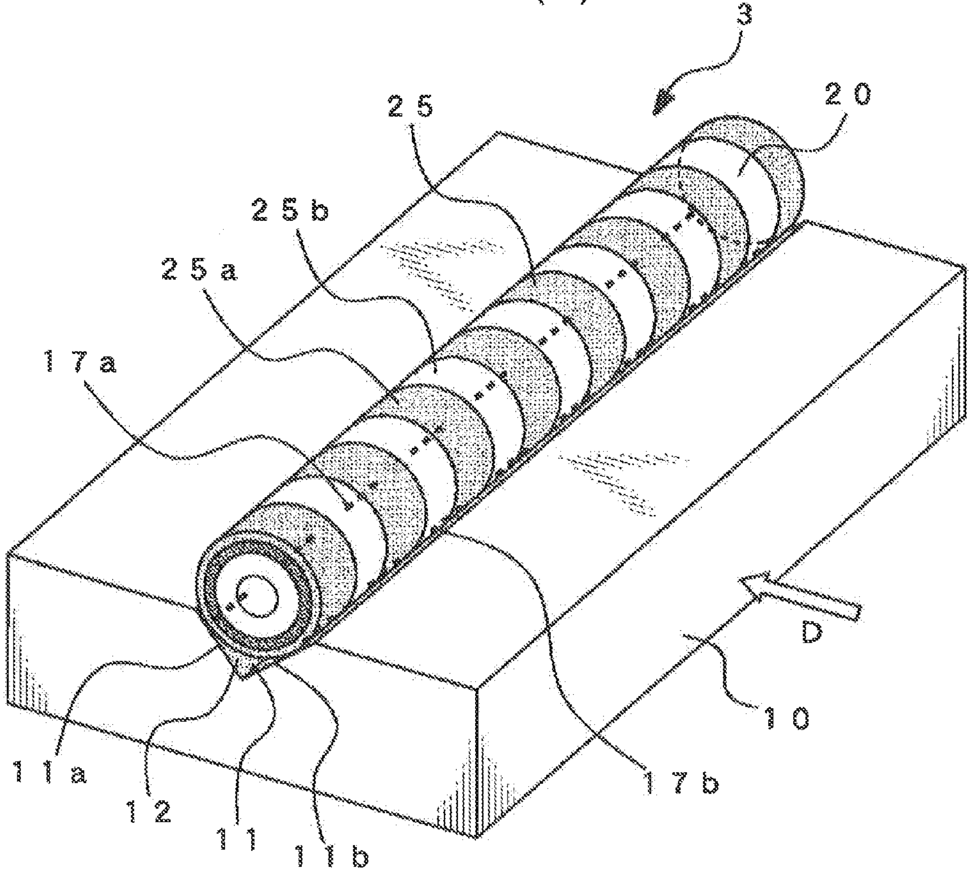


FIG.13(b)

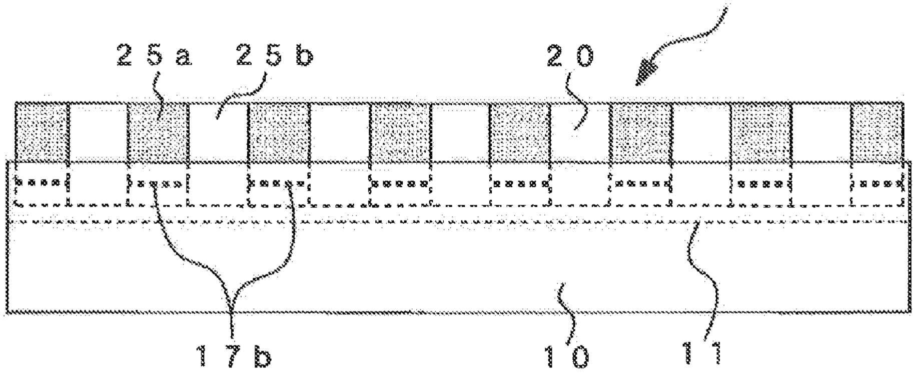


FIG.14

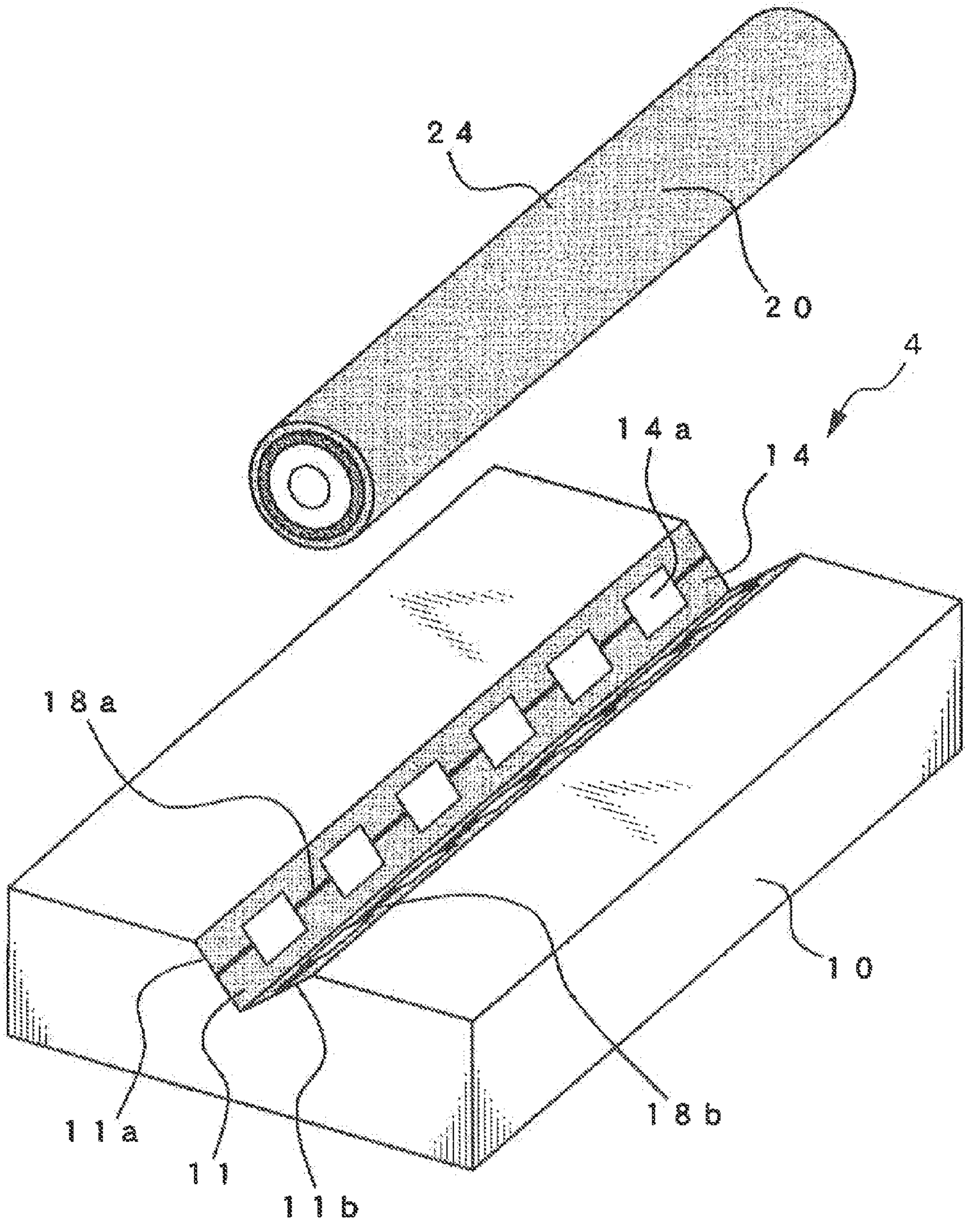


FIG.15

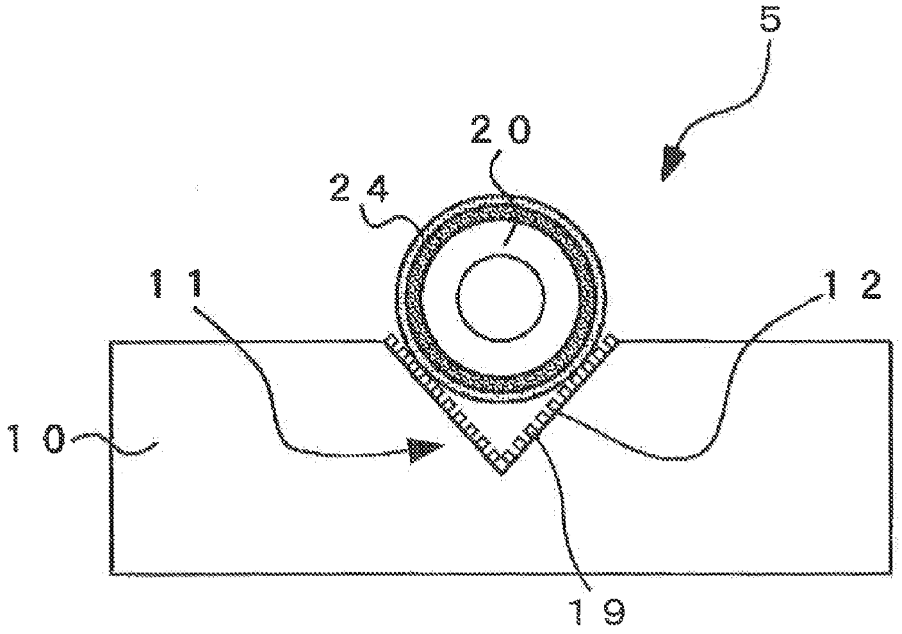


FIG.16

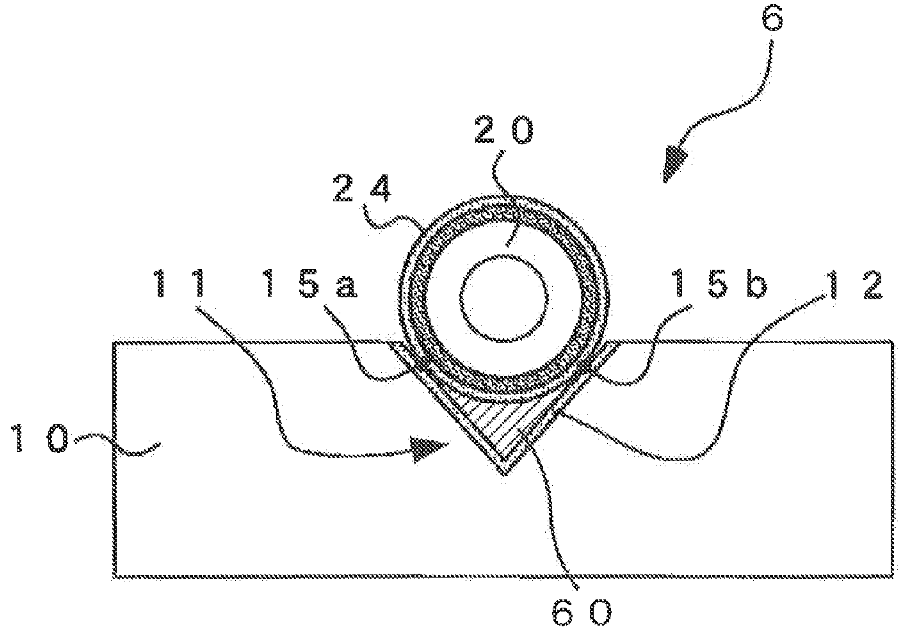


FIG.17

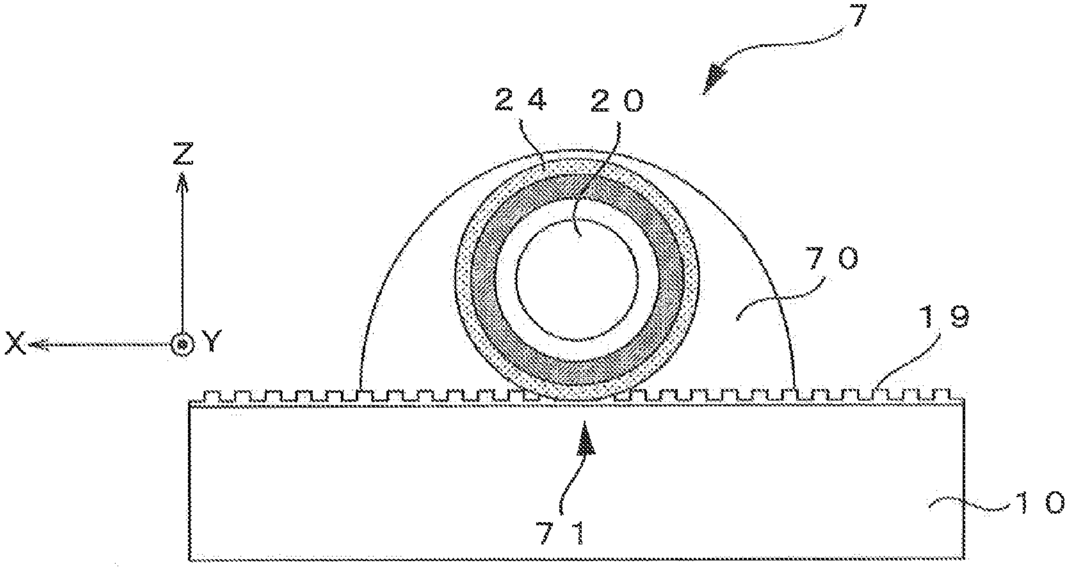
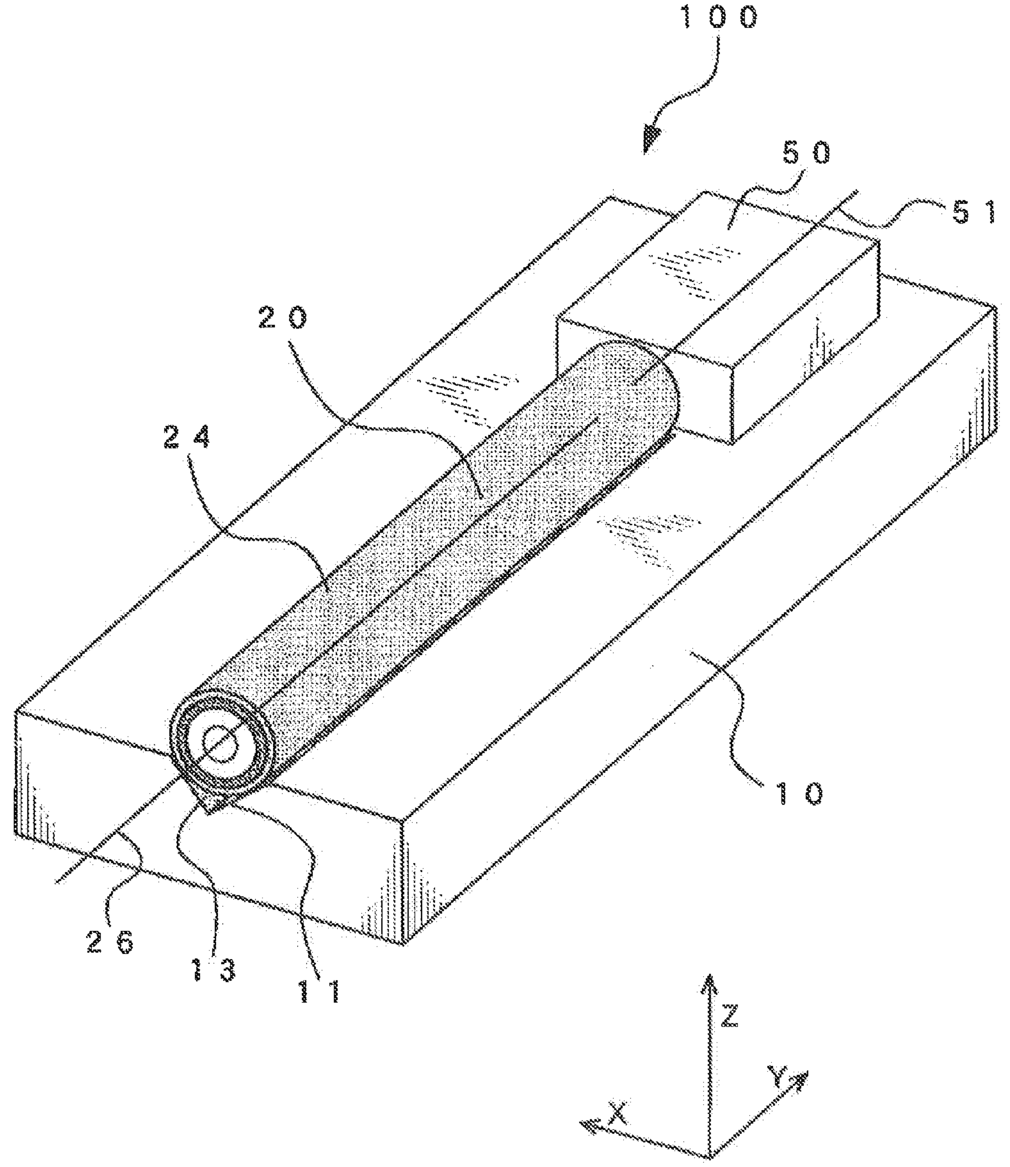


FIG.18



OPTICAL DEVICE AND METHOD FOR MANUFACUTURING THE OPTICAL DEVICE

RELATED APPLICATIONS

[0001] This application is a divisional application of U.S. application Ser. No. 13644,637, which is a U.S. patent application that claims benefit of JP 2011-219998, filed on Oct. 4, 2011, all of which is hereby incorporated by reference.

TECHNICAL FIELD

[0002] The present invention relates to an optical device manufactured by fixedly bonding an optical fiber to a substrate, and a method for manufacturing such an optical device.

BACKGROUND

[0003] In an optical device formed by mounting an optical fiber as an optical waveguide, a semiconductor laser, a wavelength conversion element, etc., on a substrate, the optical fiber and other optical elements mounted on the substrate must be aligned so as to achieve optimum optical coupling between the respective elements and then fixedly bonded to the substrate by maintaining the optimum condition.

[0004] An optical module manufacturing method is known that forms a V-shaped groove in the surface of a silicon substrate, coats the surface of the V-shaped groove as well as the surface of an optical fiber with an Au film, and presses the optical fiber onto the bottom face of the V-shaped groove to fixedly bond them together (for example, refer to Patent Document 1). In the manufacturing method of Patent Document 1, the optical fiber is fixedly bonded to the V-shaped groove by a bonding tool while heating the silicon substrate.

[0005] According to the optical module manufacturing method of Patent Document 1, the interface energy at the contact interface between the Au film on the surface of the V-shaped groove and the Au film on the surface of the optical fiber rises due to the applied heat and pressure, and interdiffusion of metal atoms between the Au film surfaces, thus bonding the Au films together. Accordingly, as Patent Document 1 describes, the optical fiber can be fixed precisely because the optical fiber is bonded to the substrate without interposing an adhesive, solder, or like layer therebetween.

[0006] Patent Document 1: JP-2817778-B (pp. 4-5, FIGS. 4-8)

SUMMARY

[0007] Since the optical module manufacturing method of Patent Document 1 uses a bonding tool for bonding the optical fiber and the silicon substrate together, it can be assumed that the silicon substrate is heated to 100° C. or higher. The heating by the bonding tool strains the silicon substrate and causes it to deform, and as a result, the optical axis of the optical fiber becomes misaligned with the optical element, resulting in a degradation of optical coupling efficiency.

[0008] Furthermore, since the Au film formed on the V-shaped groove of the silicon substrate and the Au film formed on the surface of the optical fiber are both flat in structure, the load applied to the Au films is distributed along the entire length of the V-shaped groove, and thus the applied load is insufficient, resulting in an inability to attain a desired bonding strength. Since the bonding strength between the Au films is weak, even if the semiconductor laser and the optical fiber can be aligned so as to achieve optimum optical coupling therebetween, it is difficult to maintain the optimum condition for an extended period of time.

[0009] It is an object of the present invention to provide an optical device and an optical device manufacturing method that can solve the above deficiencies.

[0010] More specifically, it is an object of the present invention to provide an optical device and an optical device manufacturing method wherein provisions are made to be able to precisely align an optical fiber relative to a substrate without heating the substrate and to maintain the optimum alignment condition for an extended period of time.

[0011] An optical device manufacturing method according to the invention includes the steps of forming a first metallic film on a portion of a substrate, forming a second metallic film on a portion of the outer circumference of an optical fiber, and bonding together the first metallic film and the second metallic film by surface activated bonding.

[0012] Preferably, the optical device manufacturing method further includes the step of forming a V-shaped groove in the surface, and the first metallic film is formed on the V-shaped groove.

[0013] Preferably, in the optical device manufacturing method, the first metallic film includes raised portions and recessed portions formed in a periodically repeating fashion along the longitudinal direction of the V-shaped groove, and the first metallic film is bonded to the second metallic film via the raised portions.

[0014] Preferably, in the optical device manufacturing method, the first metallic film includes openings formed in a periodically repeating fashion along the longitudinal direction of the V-shaped groove, and the first metallic film is bonded to the second metallic film at portions other than the openings.

[0015] Preferably, in the optical device manufacturing method, the first metallic film is formed in a stripe-shaped pattern that repeats in a periodic fashion along the longitudinal direction of the V-shaped groove.

[0016] Preferably, in the optical device manufacturing method, the second metallic film includes raised portions and recessed portions formed in a periodically repeating fashion along the longitudinal direction of the optical fiber, and the second metallic film is bonded to the first metallic film via the raised portions.

[0017] Preferably, in the optical device manufacturing method, the second metallic film includes openings formed in a periodically repeating fashion along the longitudinal direction of the optical fiber, and the second metallic film is bonded to the first metallic film at portions other than the openings.

[0018] Preferably, in the optical device manufacturing method, the second metallic film is formed in a stripe-shaped pattern that repeats in a periodic fashion along the longitudinal direction of the optical fiber.

[0019] Preferably, the optical device manufacturing method further includes the step of filling a bonding material into a gap created between the V-shaped groove and the optical fiber.

[0020] Preferably, in the optical device manufacturing method, the first metallic film, is formed on a datum plane surface of the substrate.

[0021] Preferably, the optical device manufacturing method further includes the step of fixing the optical fiber onto the substrate by using a reinforcing resin.

[0022] Preferably, in the optical device manufacturing method, the first metallic film is formed with micro-bumps.

[0023] Preferably, in the optical device manufacturing method, the first metallic film or the second metallic film is formed by laser processing a metallic film.

[0024] Preferably, in the optical device manufacturing method, the first metallic film or the second metallic film is formed by etching a metallic film.

[0025] An optical device according to the invention includes a first metallic film formed on a portion of a substrate, and a second metallic film formed on a portion of the outer circumference of an optical fiber, and wherein the optical fiber is fixedly bonded to the substrate with the first metallic film and the second metallic film bonded together by surface activated bonding.

[0026] According to the optical device and the optical device manufacturing method, the substrate and the optical fiber are fixedly bonded together by surface activated bonding that does not require heating for bonding. Accordingly, faults, such as optical axis misalignment due to the deformation of the substrate caused by heating, component breakage due to the residual stress arising from the difference in thermal expansion coefficient, and component functional degradation due to thermal stress, can be prevented from occurring.

[0027] According to the optical device and the optical device manufacturing method, it is possible to provide an optical device that achieves high optical coupling efficiency and high reliability by maintaining the optical coupling between the optical fiber and the matching optical element mounted on the same substrate in an optimum condition for an extended period of time.

[0028] According to the optical device and the optical device manufacturing method, by forming raised and recessed portions in the surface of the metallic film, the bonding strength at the contacting portions between the substrate and the optical fiber can be enhanced even when the applied load is small, because the load concentrates at the raised portions or the contacting portions other than the openings.

[0029] According to the optical device and the optical device manufacturing method, by forming raised and recessed portions in the surface of the metallic film, the adjustment range of the height of the optical fiber relative to the substrate can be enlarged, because it is possible to adjust the amount of compression of the metallic film over a wide range at the raised portions or portions other than the openings by varying the load,

BRIEF DESCRIPTION OF THE DRAWINGS

[0030] These and other features and advantages of the present invention will be better understood by reading the following detailed description, taken together with the drawings wherein:

[0031] FIG. **1** is a perspective view schematically showing the structure of an optical device **1** before a substrate and an optical fiber are bonded together;

[0032] FIG. **2** is a perspective view schematically snowing the structure of the optical device **1** after the substrate and the optical fiber are bonded together;

[0033] FIG. **3**(*a*) is a front view of the optical device **1**, and FIG. **3**(*b*) is a side view of the optical device **1** in the direction of arrow A in FIG. **3**(*a*);

[0034] FIG. **4** is a process flow diagram. showing one example of a fabrication process for the optical device **1**;

[0035] FIG. **5** is a perspective view schematically showing the structure of an alternative optical device **2** before the substrate and the optical fiber are bonded together;

[0036] FIG. **6**(*a*) is a perspective view schematically showing the structure of the alternative optical device **2** after the substrate and the optical fiber are bonded together, and FIG. **6**(*b*) is a side view in the direction of arrow C in FIG. **6**(*a*);

[0037] FIG. **7** is a process flow diagram showing one example of a process step for forming raised and recessed portions by laser processing;

[0038] FIG. **8** is a process flow diagram showing one example of a process step for forming raised and recessed portions by etching;

[0039] FIGS. **9**(*a*) and **9**(*b*) are diagrams showing a bonding step for bonding the optical fiber **20** to the silicon substrate **10** in the optical device **2**;

[0040] FIGS. **10**(*a*), **10**(*b*), and **10**(*c*) are diagrams showing how the raised and recessed portions of a first metallic film formed on the V-shaped groove of the silicon substrate are deformed under an applied load;

[0041] FIGS. **11**(*a*) and **11**(*b*) are diagrams for explaining how the height of the optical fiber is adjusted;

[0042] FIG. **12** is a perspective view schematically showing the structure of a further alternative optical device **3** before the substrate and the optical fiber are bonded together;

[0043] FIG. **13**(*a*) is a perspective view schematically showing the structure of the further alternative optical device **3** after the substrate and the optical fiber are bonded together, and FIG. **13**(*b*) is a side view in the direction of arrow D in FIG. **13**(*a*);

[0044] FIG. **14** is a perspective view schematically showing the structure of a further alternative optical device **4** before the substrate and the optical fiber are bonded together;

[0045] FIG. **15** is a diagram showing a further alternative optical device **5**;

[0046] FIG. **16** is a diagram showing a further alternative optical device **6**;

[0047] FIG. **17** is a diagram showing a further alternative optical device **7**; and

[0048] FIG. **18** is a perspective view showing a further alternative optical device **100**.

DESCRIPTION OF EMBODIMENTS

[0049] An optical device and an optical device manufacturing method according to the present invention. will be described below with reference to the drawings. It will, however, be noted that the technical scope of the present invention is not limited to the specific embodiments described herein, but extends to the inventions described in the appended claims and their equivalents.

[0050] First, an overview of surface activated bonding will be given.

[0051] Surface activated bonding is a technique that activates material surfaces by removing inactive layers, such as oxides, dirt (contaminants), etc., from the surfaces using plasma or other means to activate the surface, and that bonds the surfaces together at normal temperatures by causing atoms having high surface energy to contact each other and by utilizing the adhesion forces acting between the atoms.

[0052] Oxide films, contaminants, etc., remain adhered to the actual surfaces (the surfaces of first and second metallic films in each embodiment). Therefore, plasma cleaning or ion-beam sputter etching is performed to activate the bonding surfaces, thus putting the bonding surfaces in an activated condition in which the atoms having bonds are exposed on the surfaces. In this condition, interatomic bonding can be accomplished by merely bringing the second metallic film formed on the optical fiber into contact with the first metallic film formed on the V-shaped groove of the silicon substrate,

[0053] Since this surface activated bonding does not require heating for bonding, the following advantages are offered.

[0054] 1. Component breakage due to the residual stress arising from the difference in thermal expansion coefficient does not occur.

[0055] 2. Since components are not subjected to thermal stress, component functional degradation does not occur.

[0056] 3. Since the bonding is done in a solid phase without heating, component misalignment does not occur during mounting.

[0057] 4. No thermal effects are caused to other components.

[0058] 5. Since the atoms are directly bonded together, the bonding layer does not deteriorate over time.

[0059] FIG. **1** is a perspective view schematically showing the structure of an optical device **1** before the substrate and the optical fiber are bonded together.

[0060] A V-shaped groove **11** having a prescribed width and length is formed in the surface of the silicon substrate **10**. The surface of the V-shaped groove **11** is made up of two groove faces **11***a* and **11***b* formed opposite each other at a prescribed angle. A flat-patterned first metallic film **12** is formed to a prescribed thickness over the entire area of the two groove faces **11***a* and **11***b*. The material of the first metallic film **12** is Au (gold).

[0061] The optical fiber **20** includes a core layer **21** in the center, a clad layer **22** formed around the outer circumference of the core layer **21** and having a different refractive index, and a buffer layer **23** as a protective layer formed around the outer circumference of the clad layer **22**. A flat-patterned second metallic film **24** is formed at a prescribed thickness around the outer circumference of the optical fiber **20** so as to cover the buffer layer **23**. The material of the second metallic film **24** is also Au (gold).

[0062] The V-shaped aroove **11** of the silicon substrate **10** is formed in order to enable the optical fiber **20** to be positioned securely and bonded fixedly thereto; the width of the V-shaped groove **11** is determined according to the outer shape of the optical fiber **20** to be fitted therein, and the length of the V-shaped groove **11** is determined according to the specifications of the optical device.

[0063] FIG. **2** is a perspective view schematically showing the structure of the optical device **1** after the substrate and the optical fiber are bonded together.

[0064] The optical fiber **20** is fitted into the V-shaped groove **11** of the silicon substrate **10** and pressed thereon under a prescribed load. Thereupon, the first metallic film **12** formed on the surface of the V-shaped groove **11** and the second metallic film **24** formed on the outer circumference of the optical fiber **20** are bonded together by surface activated bonding, and the optical fiber **20** is thus bonded fixedly to the silicon substrate **10**.

[0065] The two aroove faces **11***a* and **11***b* of the V-shaped groove **11** of the silicon substrate **10** are flat faces, while the outer circumference of the optical fiber **20** is circular. Accordingly, two contacting portions **15***a* and **15***b* (in the figure, indicated by thick broken lines as if seen through the optical fiber **20**), where the first metallic film **12** formed on the V-shaped groove **11** of the silicon substrate **10** contacts the second metallic film **24** formed on the outer circumference of the optical fiber **20**, are formed extending in straight lines along the longitudinal direction of the respective groove faces **11***a* and **11***b* (in line-contacting fashion). The structure formed by fixedly bonding the silicon substrate **10** and the optical fiber **20** in integral fashion as shown in FIG. **2** is the optical device **1** manufactured by the manufacturing method to be described later.

[0066] FIG. **3**(*a*) is a front view of the optical device **1**, and FIG. **3**(*b*) is a side view of the optical device **1** in the direction of arrow A in FIG. **3**(*a*).

[0067] Since the optical fiber **20** is fitted into the V-shaped groove **11** of the silicon substrate **10** and bonded fixedly thereto, as shown in FIG. **3**(*a*), the position of the optical fiber **20** relative to the silicon substrate **10** does not become displaced, and the optical fiber **20** remains securely and fixedly bonded to the silicon substrate **10**. More specifically, the optical fiber **20** fitted into the V-shaped groove **11** of the silicon substrate **10** is fixedly bonded to it in such a manner as to be held by the two contacting portions **15***a* and **15***b*.

[0068] As shown in FIG. **3**(*b*), the optical fiber **20** is fixedly bonded along the longitudinal direction thereof with a portion of the optical fiber **20** embedded in the V-shaped groove **11** of the silicon substrate **10**. Further, since the contacting portion **15***b* (the contacting portion **15***a* is not shown in FIG. **3**(*b*)) is formed extending in a straight line along the longitudinal direction of the optical fiber **20** and the V-shaped groove **11**, the optical fiber **20** is securely and fixedly bonded along the entire length of the V-shaped groove **11**.

[0069] Furthermore, since the optical fiber **20** is bonded to the silicon substrate **10** in a line-contacting fashion so as to be held by the two contacting portions **15***a* and **15***b*, the load applied to press the optical fiber **20** is concentrated on the line contacting portions **15***a* and **15***b*. As a result, the first metallic film **12** of the silicon substrate **10** and the second metallic film **24** of the optical fiber **20** can be bonded together by surface activated bonding under a relatively small load.

[0070] FIG. **4** is a process flow diagram showing one example of a fabrication process for the optical device **1**.

[0071] The process flow diagram of FIG. **4** shows the optical device **1** as seen from the same direction as the front view of the optical device **1** (see FIG. **3**(*a*)). The process flow diagram of FIG. **4** is also applicable to an alternative fabrication process to be described later.

[0072] One feature of the manufacturing method of the optical device **1** is that the first metallic film formed on the V-shaped groove of the substrate and the second metallic film formed on the outer circumference of the optical fiber are both of a flat pattern and are bonded together by surface activated bonding.

[0073] First, the silicon substrate **10** having a prescribed thickness and treated with necessary processing is prepared (silicon substrate fabrication step S**1**).

[0074] Next, the V-shaped groove **11** with a prescribed angle is formed in the surface of the silicon substrate **10** by anisotropic etching (V-shaped groove forming step S**2**). The V-shaped groove **11** may be formed by laser processing or machining, instead of etching.

[0075] Next, the width W1 of the V-shaped groove **11** formed in the V-shaped groove forming step S**2** is measured to determine whether the V-shaped groove **11** has been formed to the desired size (V-shaped groove measuring step S**3**). The V-shaped groove measuring step S**3** is performed in order to adjust the width of the V-shaped groove **11** and thereby adjust the height of the optical axis of the optical fiber **20** relative to the surface of the silicon substrate **10**.

[0076] The height of the optical axis of the optical fiber **20** relative to the surface of the silicon substrate **10** must be adjusted to align the optical axis of the optical fiber **20** with the optical axis of a matching optical element (for example, a semiconductor laser). For this purpose, the width W**1** of the V-shaped groove **11** is measured to compute the height of the optical axis of the optical fiber **20** to be fitted into the V-shaped groove **11**. If it is determined that the V-shaped groove **11** has been formed to the desired width W**1**, the process proceeds to the next step; otherwise, the process returns to the V-shaped groove forming step S**2** to additionally process the V-shaped groove **11**.

[0077] In practice, the V-shaped groove **11** is formed to a width slightly smaller than the desired width W**1** so that the optical axis of the optical fiber **20** is set slightly higher than the desired height (at which the optical axis of the optical fiber **20** coincides with the optical axis of the matching optical element). Then, by adjusting the amount of compression of the metallic film while varying the load to be applied for bonding, the height of the optical axis of the optical fiber **20** is fine-adjusted for optical axis alignment, as will be described later.

[0078] Next, the first metallic film **12** of Au is formed to a prescribed thickness over the two groove faces **11***a* and **11***b* of the V-shaped groove **11** formed in the surface of the silicon substrate **10** (first metallic film forming step S**4**). The first metallic film **12** is formed by such means as vapor deposition or plating.

[0079] Next, the optical fiber **20** is prepared (optical fiber fabrication step S**5**). The optical fiber **20** is made up of the core layer **21**, clad layer **22**, and buffer layer **23**. The buffer layer **23** is provided to enhance the adhesion and hermeticity of the silica-based optical fiber relative to the second metallic film **24** in order to produce a metallized fiber by coating the surface of the optical fiber **20** with the second metallic film. The buffer layer **23** can be formed from a single layer of an Ni-plated film or Ti-sputtered film or from a metallic layer of a two-layered structure formed by depositing an Ni-plated or Ni-sputtered film on top of a Ti-sputtered film.

[0080] Next, the second metallic film **24** of Au is formed to a prescribed thickness around the outer circumference of the optical fiber **20** (second metallic film forming step S**6**). The second metallic film **24** is formed by such means as sputtering, vapor deposition, or plating.

[0081] Next, before bonding the optical fiber **20** to the silicon substrate **10**, the first metallic film **12** formed on the V-shaped groove **11** of the silicon substrate **10** and the second metallic film **24** formed around the outer circumference of the optical fiber **20** are cleaned with argon plasma to activate their surfaces. After that, the optical fiber **20** coated with the second metallic film **24** is fitted into the V-shaped groove **11** of the silicon substrate **10** coated with the first metallic film **24**, and the two members are pressed together under a prescribed load, thereby bonding the first metallic film **12** and the second metallic film **24** by surface activated bonding (bonding step S**7**). The optical fiber **20** is thus bonded fixedly to the silicon substrate **10**, completing the fabrication of the optical device **1** with the optical fiber **20** mounted on the silicon substrate **10**.

[0082] After the bonding step S**7** and/or a subsequent fine-adjusting step, the optical fiber **20** is optically coupled to other optical elements (semiconductor laser, wavelength conversion element, etc.) (not shown) in a suitable manner. Preferably, other optical elements are properly positioned on the silicon substrate **10** and fixed to it in advance.

[0083] According to the optical device manufacturing method described above, the silicon substrate **10** and the optical fiber **20** are bonded together by surface activated bonding that does not require heating for bonding. Accordingly, faults, such as optical axis misalignment due to the deformation of the substrate caused by heating, component breakage due to the residual stress arising from the difference in thermal expansion coefficient, and component functional degradation due to thermal stress, can be prevented from occurring. It is thus possible to provide an optical device that achieves high optical coupling efficiency and high reliability by maintaining the optical coupling between the optical fiber and its matching optical element in an optimum condition for an extended period of time. Furthermore, in the optical device **1**, since the first metallic film **12** and the second metallic film **24** are both of a flat pattern, the formation of the metallic films is simple, which offers the advantage of being able to simplify the optical device fabrication process.

[0084] FIG. **5** is a perspective view schematically showing the structure of an alternative optical device **2** before the substrate and the optical fiber are bonded together. In FIG. **5**, the same component elements as those in FIG. **1** are designated by the same reference numerals, and the description of such component elements will not be repeated here.

[0085] As shown in FIG. **5**, the V-shaped groove **11** having a prescribed width and length is formed in the surface of the silicon substrate **10**, and a first metallic film **13** with stripe-shaped raised and recessed portions formed in a periodically repeating fashion along the longitudinal direction of the V-shaped groove **11** is formed on the surface of the V-shaped groove **11**. The material of the first metallic film **13** is Au.

[0086] In the figure showing the stripe-shaped raised and recessed portions of the first metallic film **13**, the portions lightly shaded are the raised portions **13***a*, and the portions not shaded are the recessed portions **13***b*. The thickness of the first metallic film **13** differs between the raised portions **13***a* and the recessed portions **13***b*; i.e., the portions where the metallic film (Au) is thick are the raised portions **13***a*, and the portions where the metallic film (Au) is thin are the recessed portions **13***b*. The raised portions **13***a* and the recessed portions **13***b* are formed in a stripe-shaped pattern repeating in a periodic fashion along the longitudinal direction of the V-shaped groove **11**. The recessed portions **13***b* may be formed by removing the metallic film and exposing the surface of the silicon substrate **10**. In this case, the first metallic film **13** is formed only from the raised portions **13***a*.

[0087] The optical fiber **20** is the same as used in the optical. device **1** and will not be described in detail, except that the outer circumference of the optical fiber **20** is coated with the flat-patterned second metallic film **24**. The material of the second metallic film **24** is Au. Cross section line B-B' will be described later.

[0088] FIG. **6**(*a*) is a perspective view schematically showing the structure of the alternative optical device **2** after the substrate and the optical fiber are bonded together, and FIG. **6**(*b*) is a side view in the direction of arrow C in FIG. **6**(*a*).

[0089] As shown in FIGS. **6**(*a*) and **6**(*b*), the optical fiber **20** is fitted into the V-shaped groove **11** of the silicon substrate **10** and pressed thereon under a prescribed load. Thereupon, the first metallic film **13** having raised and recessed portions formed on the surface of the V-shaped groove **11** and the flat-patterned second metallic film **24** formed on the outer circumference of the optical fiber **20** are bonded together by surface activated bonding, and the optical fiber **20** is thus bonded fixedly to the silicon substrate **10**.

[0090] The two groove faces **11***a* and **11***b* of the V-shaped groove **11** of the silicon substrate **10** are flat faces, while the outer circumference of the optical fiber **20** is circular. Accordingly, two contacting portions **16***a* and **16***b* (in the figure, indicated by thick broken lines as if seen through the optical fiber **20**), where the first metallic film **13** formed on the V-shaped groove **11** of the silicon substrate **10** contacts the second metallic film **24** formed on the outer circumference of the optical fiber **20**, are formed at prescribed intervals in a discontinuous manner along the longitudinal direction of the respective groove faces **11***a* and **11***b*.

[0091] Since the first metallic film **13** on the V-shaped groove **11** is provided with the stripe-shaped raised and recessed portions formed in a periodically repeating fashion, as earlier described, the second metallic film **24** of the optical fiber **20** contacts the first metallic film **13** only at the raised portions **13***a* thereof and does not contact at the recessed portions **13***b*. Accordingly, the two contacting portions **16***a* and **16***b* are each located in a discontinuous manner in the regions of the raised portions **13***a* formed in a periodically repeating fashion.

[0092] As shown in FIG. **6**(*b*), in the optical device **2**, as in the optical device **1**, the optical fiber **20** is fixedly bonded along the longitudinal direction thereof with a portion of the optical fiber **20** embedded in the V-shaped groove **11** of the silicon substrate **10**. Therefore, the contacting portion **16***b* (in the figure, the contacting portion **16***a* is not shown) is formed at prescribed intervals in a discontinuous manner along the longitudinal direction of the optical fiber **20** and the V-shaped groove **11**.

[0093] In this way, the optical fiber **20** in the optical device **2** contacts the silicon substrate **10** at the discontinuously formed contacting portions **16***a* and **16***b*, i.e., the raised portions **13***a* formed in a periodically repeating fashion. Accordingly, in the optical device **2**, the contact is close to a multiple-point contact, and therefore, the contact area is much smaller than in the case of the optical device **1**. As a result, since the load applied when bonding the optical fiber **20** to the silicon substrate **10** is further concentrated at the contacting portions **16***a* and **16***b* that are close to point contacts, the silicon substrate **10** and the optical fiber **20** can be bonded together by surface activated bonding under a load smaller than that required in the case of the optical fiber **1**.

[0094] In the optical device **2**, if approximately the same load as that used in the bonding step of the optical device **1** is applied for bonding, the bonding strength can be further increased, since the large load concentrates at the contacting portions **16***a* and **16***b*. The structure formed by fixedly bonding the silicon substrate **10** and the optical fiber **20** in integral fashion as shown in FIG. **6** is the optical device **2** manufactured by the manufacturing method to be described later.

[0095] In FIG. **5**, the stripe-shaped raised and recessed portions **13***a* and **13***b* of the first metallic film **13** are each shown as being formed across the entire width of the interior surface of the V-shaped groove **11**, but alternatively, the raised and recessed portions **13***a* and **13***b* may be formed only at and near the contacting portions **16***a* and **16***b* that contact the second metallic film **24** of the optical fiber **20**. In that case, the regions other than the contacting portions **16***a* and **16***b* may be covered with a flat-patterned metallic film or may not be covered with any metallic film. That is, the raised and recessed portions of the first metallic film **13** need only be formed along the contacting portions **16***a* and **16***b* that contact the second metallic film **24** of the optical fiber **20**. Furthermore, the raised and recessed portions of the first metallic film **13** need not necessarily be formed in a stripe pattern, but may be formed in any suitable pattern, the only requirement is that the raised and recessed portions be formed in a periodically repeating fashion.

[0096] The fabrication process of the optical device **2** is the same as the fabrication process of the optical device **1** described earlier (see FIG. **4**), except the step for forming the raised and recessed portions in the first metallic film **13** of the silicon substrate **10** and the bonding step for bonding the optical fiber **20** to the silicon substrate **10**; therefore, the other steps will not be further described herein. The step for forming the raised and recessed portions in the first metallic film forming step S**4** of FIG. **4** will be described in detail below.

[0097] One feature of the manufacturing method of the optical device **2** is that the first metallic film formed on the V-shaped groove of the substrate, with the stripe-shaped raised and recessed portions formed in a periodically repeating fashion, and the second metallic film formed on the outer circumference of the optical fiber are bonded together by surface activated bonding.

[0098] FIG. **7** is a process flow diagram showing one example of the step for forming the raised and recessed portions by laser processing. A cross-sectional view taken along line B-B' in FIG. **5** is shown in FIG. **7**. Since the step of forming the raised and recessed portions is a step added to the first metallic film forming step S**4** in the fabrication process shown in FIG. **4**, the sequence of process steps will be described below as steps S**40** to S**42**.

[0099] First, the V-shaped groove **11** is formed by anisotropic etching in the surface of the silicon substrate **10** planarized by a CMOS-LSI forming process, etc., and the first metallic film **13** is formed by uniformly depositing Au by vapor deposition on the surface of the V-shaped groove **11** (first metallic film forming step S**40**). The V-shaped groove **11** may be formed by a method other than anisotropic etching, and the first metallic film **13** may be formed by a method other than vapor deposition.

[0100] Next, the raised and recessed portions are formed in the surface of the first metallic film **13** by laser processing (laser processing start step S**41**). To form the stripe-shaped raised and recessed portions in a periodically repeating fashion along the longitudinal direction of the V-shaped groove of the silicon substrate **10**, laser light **41** is repeatedly radiated for a predetermined period of time while moving a laser processing tool **40** along the longitudinal direction (arrow E) of the V-shaped groove **11**, thereby removing a portion of Au from the surface of the first metallic film **13** to reduce the thickness of that portion. Regions irradiated with the laser light **41** form the recessed portions **13***b*, and regions not irradiated with the laser light **41** form the raised portions **13***a*.

[0101] Next, the laser light **41** is repeatedly radiated while moving the laser processing tool **40** and, when the laser processing tool **40** reaches the end of the longitudinal direction of the V-shaped groove **11**, and the raised portions **13***a* and the recessed portions **13***b* are formed in a periodically repeating fashion over the entire area of the V-shaped groove **11**, the laser processing step ends (laser processing end step S**42**). By thus carrying out the laser processing start step S**41** and the laser processing end step S**42**, the raised portions **13***a* where the thickness of the first metallic film **13** is retained and the recessed portions **13***b* where the thickness of the first metallic film **13** is reduced by laser processing are formed in a stripe-shaped pattern in the surface of the V-shaped groove **11** of the silicon substrate **10**. The depth of the recessed portions **13***b* can be adjusted by varying the radiation time, etc., of the laser light **41**.

[0102] FIG. **8** is a process flow diagram showing one example of the step for forming the raised and recessed portions by etching. A cross-sectional view taken along line B-B' in FIG. **5** is shown in FIG. **8**. Since the step of forming the raised and recessed portions is a step added to the first metallic film forming step S**4** in the fabrication process shown in FIG. **4**, the sequence of process steps will be described below as steps S**43** to S**45**. The process shown in FIG. **8** can be used instead of the process shown in FIG. **7**.

[0103] First, the V-shaped groove **11** is formed by anisotropic etching in the surface of the silicon substrate **10** planarized by a CMOS-LSI forming process, etc., and the first metallic film **13** is formed by uniformly depositing Au by vapor deposition on the surface of the V-shaped groove **11** (first metallic film forming step S**43**). The V-shaped groove **11** may be formed by a method other than anisotropic etching, and the first metallic film **13** may be formed by a method other than vapor deposition.

[0104] Next, a resist film **30** for forming the raised and recessed portions is formed on the surface of the first metallic film **13** (resist forming step S**43**). To form the stripe-shaped raised and recessed portions in a periodically repeating fashion along the longitudinal direction of the V-shaped groove **11** of the silicon substrate **10**, the resist film **30** is formed in a pattern of periodically repeating stripes so as to cover the regions where the raised portions are to be formed but not cover the regions where the recessed portions are to be formed.

[0105] Next, the portions of the first metallic film **13** that are not covered with the resist film **30** are etched (etching step S**44**). The thus etched portions form the recessed portions **13***b*.

[0106] Next, the resist film **30** is removed (resist removing step S**45**). Since the portions covered with the resist film **30** remain unetched, the original thickness of the first metallic film **13** is retained in the unetched portions which thus form the raised portions **13***a*. In this way, the raised portions **13***a* where the thickness of the first metallic film **13** is retained and the recessed portions **13***b* where the thickness of the first metallic film **13** is reduced by etching are formed on the surface of the V-shaped groove **11** of the silicon substrate **10**. The depth of the recessed portions **13***b* can be adjusted by varying the etching time, etc.

[0107] FIGS. **9**(*a*) and **9**(*b*) are diagrams showing the bonding step for bonding the optical fiber **20** to the silicon substrate **10** in the optical device **2**.

[0108] As shown in FIG. **9**(*a*), the first metallic film **13** is formed on the surface of the V-shaped groove **11** of the silicon substrate **10**, and the raised portions **13***a* and the recessed portions **13***b* are formed in the first metallic film **13** in a periodically repeating fashion along the longitudinal length of the V-shaped groove **11**.

[0109] The flat-patterned second metallic film **24** is formed around the outer circumference of the optical fiber **20**. A pressing tool **42** is pressed onto the optical fiber **20** from the top in the figure. Preferably, the pressing tool **42** has such a structure as no press the optical fiber **20** substantially along the entire length of the V-shaped groove **11** of the silicon substrate **10**. With this structure, the optical fiber **20** can be pressed uniformly along the entire length of the V-shaped groove **11** of the silicon substrate **10**.

[0110] With the pressure applied by the pressing tool **42**, the first metallic film **13** formed on the silicon substrate **10** and the second metallic film **24** formed on the optical fiber **20** are bonded together by the surface activation method described earlier. Before bonding, the first metallic film **13** and the second metallic film **24** are cleaned with argon plasma (not shown) to activate their surfaces.

[0111] Next, the optical fiber **20** is positioned and fitted into the V-shaped groove **11** of the silicon substrate **10**, as shown in FIG. **9**(*b*), and a prescribed load K is applied to the optical fiber **20** by means of the pressing tool **42**. As the load is thus applied, the first metallic film **13** formed on the silicon substrate **10** and the second metallic film **24** formed on the optical fiber **20** are bonded together by surface activated bonding.

[0112] As described above, the raised portions **13***a* and the recessed portions **13***b* are formed in the first metallic film **13** on the surface of the V-shaped groove **11** of the silicon substrate **10**. Accordingly, when the optical fiber **20** is fitted into the V-shaped groove **11** and pressed thereon, the second metallic film **24** formed on the outer circumference of the optical fiber **20** contacts the first metallic film **13** only at the raised portions **13***a* thereof. Since the load K from the optical fiber **20** concentrates at the raised portions **13***a*, the Au in the raised portions **13***a* and the Au in the second metallic film **24** contacting the raised portions **13***a* are bonded together by interatomic bonding at normal temperatures even when the applied load is relatively small. The optical fiber **20** is thus bonded fixedly to the silicon substrate **10** by surface activated bonding.

[0113] FIG. **10** is a diagram showing how the raised and recessed portions of the first metallic film formed on the V-shaped groove of the silicon substrate are deformed under an applied load. FIG. **10** is a side view showing a portion of the side view of FIG. **9** in enlarged form.

[0114] FIG. **10**(*a*) shows the condition before the optical fiber **20** is pressed onto the silicon substrate **10**. In FIG. **10**(*a*), the height of the raised portions **13***a* of the first metallic film **13** formed on the surface of the V-shaped groove **11** of the silicon snbstrate **10** is denoted by h0, and the width of each raised portion **13***a* is denoted by F0.

[0115] As shown in FIG. **10**(*b*), when the optical fiber **20** is pressed by the pressing tool **42** (see FIG. **9**) onto the V-shaped groove **11** of the silicon substrate **10** under a load K1, the second metallic film **24** of the optical fiber **20** contacts the raised portions **13***a* of the first metallic film **13**, and thus the raised portions **13***a* are pushed downward. Since the raised portions **13***a* are compressed and deformed under pressure and spread into the adjacent recessed portions **13***b*, the height of the raised portions **13***a* is reduced (to height h1) while the width of each raised portion **13***a* is enlarged (to width F1).

[0116] In the case of FIG. **10**(*b*), the optical fiber **20** is bonded fixedly to the silicon substrate **10** by surface activated bonding under the pressure of the load applied by the pressing tool **42**; since the raised portions **13***a* of the first metallic film **13** are maintained in the compressed condition, the height of the raised portions **13***a* is held at h1.

[0117] FIG. **10**(*c*) shows the condition in which the optical fiber **20** is pressed by the pressing tool **42** (see FIG. **9**) onto the V-shaped groove **11** of the silicon substrate **10** under a load K2 which is larger than the load K1. In this case, since the raised portions **13***a* are further compressed and deformed under pressure and spread into the adjacent recessed portions

13*b*, the height of the raised portions **13***a* is further reduced (to height h2) while the width of each raised portion **13***a* is further enlarged (to width F2).

[0118] In the case of FIG. **10**(*c*), the optical fiber **20** is bonded fixedly to the silicon substrate **10** by surface activated bonding under the pressure of the load applied by the pressing tool **42**; since the raised portions **13***a* of the first metallic film **13** are maintained in the compressed condition, the height of the raised portions **13***a* is held at h2.

[0119] In this way, the silicon substrate **10** and the optical fiber **20** are bonded together by surface activated bonding at normal temperatures under the pressure of the prescribed load applied thereto. Further, by adjusting the magnitude of the load to be applied to the optical fiber **20** for bonding, the height h of the raised portions **13***a* of the first metallic film **13** can be varied. The fact that the height h of the raised portions **13***a* of the first metallic film **13** can be varied means that the height of the optical fiber **20** relative to the silicon substrate **10** can be adjusted. This in turn means that the optical axis of the optical fiber **20** can be precisely aligned with the optical axis of the matching optical element (such as the semiconductor laser) mounted on the same silicon substrate **10**.

[0120] FIG. **11** is a diagram for explaining how the height of the optical fiber is adjusted.

[0121] When the optical fiber **20** is pressed onto the V-shaped groove **11** of the silicon substrate **10** under the relatively small load K1, as shown in FIG. **11**(*a*), the amount of compression of the raised portions **13***a* of the first metallic film **13** (see FIG. **10**) is relatively small. Accordingly, the height H1 from the surface of the silicon substrate **10** to the optical axis **26** at the center of the optical fiber **20** is relatively high.

[0122] On the other hand, when the optical fiber **20** is pressed onto the V-shaped groove **11** of the silicon substrate **10** under the relatively large load K2, as shown in FIG. **11**(*b*), the amount of compression of the raised portions **13***a* of the first metallic film **13** (see FIG. **10**) increases. Accordingly, the height H2 from the surface of the silicon substrate **10** to the optical axis **26** at the center of the optical fiber **20** is relatively low.

[0123] In this way, by varying the magnitude of the load applied to effect the surface activated bonding of the silicon substrate **10** and the optical fiber **20**, the height H of the optical axis **26** of the optical fiber **20** relative to the silicon substrate **10** can be adjusted as desired. Since the height of the optical fiber **20** can be adjusted by varying the magnitude of the load, the optical axis can be highly precisely aligned with the optical axis of the matching optical element mounted on the same silicon substrate **10**. It is thus possible to manufacture a high-performance optical device that can adjust the optical coupling between the optical elements to an optimum condition and that can maintain the optimum condition for an extended period of time.

[0124] In the case of the optical device **1** shown in FIGS. **1** to **4** in which the flat-patterned metallic films are bonded together, it is also possible to adjust the height of the optical fiber **20** by varying the magnitude of the load. However, in the case of the optical device **2** shown in FIGS. **5** to **10** in which one of the metallic films is formed with raised and recessed portions, the contact portions close to point contacts are formed, and the load can therefore be concentrated at the raised portions **13***a*. Furthermore, when the raised portions **13***a* are compressed and deformed under the pressure of the load, the Au forming each raised portion **13***a* is allowed to spread into its adjacent recessed portions **13***b*, thus making it possible to increase the amount by which the raised portion **13***a* is compressed. Accordingly, in the case of the optical device **2**, the range over which the height of the optical axis of the optical fiber **20** can be adjusted by the compression of the raised portions **13***a* by varying the magnitude of the load can be enlarged compared with the case of the optical device **1**.

[0125] As a result, in the optical device **2**, if the amount of misalignment between the optical fiber **20** and the optical axis of its matchind optical element is relatively large, the height of the optical axis of the optical fiber **20** can be adjusted by an amount large enough to correct such an alignment error; in this way, a high-performance optical device having high optical coupling efficiency can be achieved.

[0126] FIG. **12** is a perspective view schematically showing the structure of a further alternative optical device **3** before the substrate and the optical fiber are bonded together. In FIG. **12**, the same component elements as those in FIG. **1** are designated by the same reference numerals, and the description of such component elements will not be repeated.

[0127] In FIG. **12**, the V-shaped groove **11** having a prescribed width and length is formed in the surface of the silicon substrate **10**, and the flat-patterned first metallic film **12** is formed on the surface of the V-shaped groove **11**, as in the case of the optical device **1**. The material of the first metallic film **13** is Au.

[0128] A second metallic film **25** with stripe-shaped raised and recessed portions formed in a periodically repeating fashion along the longitudinal direction of the optical fiber **20** is formed around the outer circumference of the optical fiber **20**. The material of the second metallic film **25** is Au.

[0129] In the figure showing the stripe-shaped raised and recessed portions of the second metallic film **25**, the portions lightly shaded are the raised portions **25***a*, and the portions not shaded are the recessed portions **25***b*. The thickness of the second metallic film **25** differs between the raised portions **25***a* and the recessed portions **25***b*; i.e., the portions where the metallic film (Au) is thick are the raised portions **25***a*, and the portions where the metallic film (Au) is thin are the recessed portions **25***b*. The raised portions **25***a* and the recessed portions **25***b* are formed in a stripe-shaped pattern repeating in a periodic fashion along the longitudinal direction of the optical fiber **20**.

[0130] According to the pattern of the second metallic film **25**, the stripe-shaped raised and recessed portions of the second metallic film **25** can be made to contact the V-shaped groove **11** of the silicon substrate **10**, regardless of how the optical fiber **20** is rotated relative to the silicon substrate **10**. The recessed portions **25***b* may be formed by removing the second metallic film **25** and exposing the underlying buffer layer **23** of the optical fiber **20**. In this case, the second metallic film **25** is formed only from the raised portions **25***a*.

[0131] FIG. **13**(*a*) is a perspective view schematically showing the structure of the further alternative optical device **3** after the substrate and the optical fiber are bonded together, and FIG. **13**(*b*) is a side view in the direction of arrow D in FIG. **13**(*a*).

[0132] As shown in FIGS. **13**(*a*) and **13**(*b*), the optical fiber **20** is fitted into the V-shaped groove **11** of the silicon substrate **10** and pressed thereon under a prescribed load. Thereupon, the flat-patterned first metallic film **12** formed on the surface of the V-shaped groove **11** and the second metallic film **25** having raised and recessed portions formed on the outer circumference of the optical fiber **20** are bonded together by surface activated bonding, and the optical fiber **20** is thus bonded fixedly to the silicon substrate **10**.

[0133] The two groove faces **11***a* and **11***b* of the V-shaped groove **11** of the silicon substrate **10** are flat faces, while the outer circumference of the optical fiber **20** is circular. Accordingly, two contacting portions **17***a* and **17***b* (in the figure, indicated by thick broken lines as if seen through the optical fiber **20**), where the first metallic film **12** formed on the V-shaped groove **11** of the silicon substrate **10** contacts the second metallic film **25** formed on the outer circumference of the optical fiber **20**, are formed at prescribed intervals in a discontinuous manner along the longitudinal direction of the respective groove faces **11***a* and **11***b*.

[0134] The second metallic film **25** on the outer circumference of the optical fiber **20** is provided with the stripe-shaped raised and recessed portions formed in a periodically repeating fashion, as earlier described. Therefore, the first metallic film **12** actually contacts the second metallic film **25** of the optical fiber **20** only at the raised portions **25***a* thereof and does not contact at the recessed portions **25***b*. Accordingly, the two contacting portions **17***a* and **17***b* are each located in a discontinuous manner in the regions of the raised portions **25***a* formed in a periodically repeating fashion,

[0135] As shown in FIG. **13**(*b*), as in the optical device **1**, the optical fiber **20** is fixedly bonded along the longitudinal direction thereof with a portion of the optical fiber **20** embedded in the V-shaped groove **11** of the silicon substrate **10**. The contacting portion **17***b* (in the figure, the contacting portion **17***a* is not shown) is formed at prescribed intervals in a discontinuous manner along the longitudinal direction of the optical fiber **20** and the V-shaped groove **11**. The structure formed by fixedly bonding the silicon substrate **10** and the optical fiber **20** in integral fashion as shown in FIG. **13** is the optical device **3** manufactured by the manufacturing method to be described later.

[0136] As described above, in the optical device **3**, the contact between the silicon substrate **10** and the optical fiber **20** is close to a multiple-point contact, as in the case of the optical device **2**. As a result, since the load applied for bonding is further concentrated at the contacting portions **17***a* and **17***b* that are close to point contacts, the silicon substrate **10** and the optical fiber **20** can be bonded together by surface activated bonding under a load smaller than that required in the case of the optical fiber **1**. Further, in the optical device **3**, if approximately the same load as that used in the bonding step of the optical device **1** is applied for bonding, the bonding strength can be further increased, since the large load is concentrated at the contacting portions **17***a* and **17***b*.

[0137] The pattern of the raised and recessed portions of the second metallic film **25** of the optical fiber **20** need not be limited to the stripe-shaped pattern. The pattern of the raised and recessed portions of the second metallic film **25** of the optical fiber **20** may be formed in any suitable pattern, the only requirement is that they be formed in a periodically repeating fashion along the portions where the second metallic film **25** contacts the first metallic film **12** of the silicon substrate **10**.

[0138] The fabrication process of the optical device **3** is the same as the fabrication process of the optical device **1** described earlier (see FIG. **4**), except the step for forming the raised and recessed portions in the second metallic film **25** on the outer circumference of the optical fiber **20** and the bonding step for bonding the optical fiber **20** to the silicon substrate **10**; therefore, the other steps will not be further described herein. The step for forming the raised and recessed portions in the second metallic film **25** on the outer circumference of the optical fiber **20** is added in the second metallic film forming step S**6** shown in FIG. **4**, but the details of the step are essentially the same as those of the raised/recessed portion forming step of the optical device **2** described earlier (laser processing step (see FIG. **7**) or etching step (see FIG. **8**)).

[0139] One feature of the manufacturing method of the optical device **3** is that the flat-patterned first metallic film formed on the V-shaped groove of the substrate and the second metallic film formed on the outer circumference of the optical fiber, with the stripe-shaped raised and recessed portions formed in a periodically repeating fashion, are bonded together by surface activated bonding.

[0140] The bonding step S**7** for bonding the optical fiber **20** to the silicon substrate **10** (including the height adjustment of the optical fiber) in the optical device **3** is essentially the same as the bonding step of the optical device **2** (see FIGS. **9** to **11**), the only difference being where the raised and recessed portions are formed (the silicon substrate **10** or the optical fiber **20**), and therefore, the description will not be repeated here. Further, the effect achieved by forming the raised and recessed portions in the second metallic film **25** on the outer circumference of the optical fiber **20** is the same as that achieved by forming the raised and recessed portions in the surface of the first metallic film **13** of the optical device **2**.

[0141] FIG. **14** is a perspective view schematically showing the structure of a further alternative optical device **4** before the substrate and the optical fiber are bonded together. In FIG. **14**, the same component elements as those in FIG. **1** are designated by the same reference numerals, and the description of such component elements will not be repeated here.

[0142] In FIG. **14**, the V-shaped groove **11** of a prescribed size is formed in the surface of the silicon substrate **10**, and a first metallic film **14** having a plurality of rectangular openings **14***a* formed in a periodically repeating fashion along the longitudinal direction of the V-shaped groove **11** is formed on the surface of the V-shaped groove **11**. The material of the first metallic film **14** is Au.

[0143] The openings **14***a* in the first metallic film **14** are each formed by removing the metallic film and exposing the surface of the V-shaped groove **11** of the silicon substrate **10**, but need not necessarily be limited to this specific structure; for example, the openings **14***a* may each be covered with a metallic film thinner than the first metallic film **14** forming the entire region other than the openings.

[0144] As in the optical device **1**, the outer circumference of the optical fiber **20** is covered with the flat-patterned second metallic film **24**. The material of the second metallic film **24** is Au.

[0145] The optical fiber **20** is fitted into the V-shaped groove **11** of the silicon substrate **10** and pressed thereon under a prescribed load. Thereupon, the first metallic film **14** formed on the surface of the V-shaped groove **11** and the second metallic film **24** formed on the outer circumference of the optical fiber **20** are bonded together by surface activated bonding, and the optical fiber **20** is thus bonded fixedly to the silicon substrate **10**.

[0146] Contacting portions **18***a* and **18***b* (indicated by thick lines) where the optical fiber **20** contacts the silicon substrate **10** are formed at prescribed intervals in a discontinuous manner along the longitudinal direction of the respective groove faces **11***a* and **11***b* of the V-shaped groove **11**, as in the case of the optical device **2**. As described above, the first metallic film

14 is provided with the rectangular openings **14***a* formed in a periodically repeating fashion along the longitudinal direction of the V-shaped groove **11**. Therefore, the second metallic film **24** of the optical fiber **20** actually contacts the first metallic film **14** only at regions other than the regions of the openings **14***a*. Accordingly, the two contacting portions **18***a* and **18***b* are each located in a discontinuous manner in the regions other than the regions of the openings **14***a*.

[0147] As described above, in the optical device **4**, the rectangular openings **14***a* are formed on the surface of the V-shaped groove **11** of the silicon substrate in a periodically repeating fashion along the longitudinal direction of the V-shaped groove **11**. Further, the two contacting portions **18***a* and **18***b* where the optical fiber **20** in the optical device **4** contacts the V-shaped groove **11** are similar to the two contacting portions **16***a* and **16***b* formed in the optical device **2**. As a result, when the load is applied to the optical fiber **20** in the bonding step, the load concentrates at the contacting portions **18***a* and **18***b* formed in the regions other than the regions of the openings **14***a*; therefore, the optical fiber **20** can be fixedly bonded even when the applied load is relatively small.

[0148] When the metallic film in the contact area is compressed under the load concentrated at the contacting portions **18***a* and **18***b*, the metallic film is allowed to spread into its adjacent openings **14***a*. Accordingly, in common with the optical device **2**, the optical device **4** offers the excellent advantage that the adjustment range of the height of the optical axis of the optical fiber **20** relative to the silicon substrate **10** can be enlarged by increasing the amount by which the area other than the openings **14***a* can be compressed. The shape of each opening **14***a* need not be limited to a rectangle, but may be formed, for example, in a circular shape.

[0149] In the optical device **4**, the openings **14***a* can be formed by laser processing or by etching in the same manner as the process step for forming the raised and recessed portions in the optical device **2** (see FIGS. **7** and **8**), and therefore, the details of the process step will not be described herein. Further, in the optical device **4**, the bonding step for bonding the optical fiber **20** to the silicon substrate **10** and the step for adjusting the height of the optical fiber **20** are the same as the corresponding steps in the optical **2** (see FIGS. **9** to **11**), and therefore, the details of these process steps will not be described herein.

[0150] In the optical device **4**, the first metallic film **14** having the openings **14***a* is formed on the V-shaped groove **11** of the silicon substrate **10**, and the flat-patterned second metallic film **24** is formed around the outer circumference of the optical fiber **20**, but the optical device **4** is not limited to this specific structure; for example, the flat-patterned first metallic film may be formed on the V-shaped groove **11** of the silicon substrate **10**, and the second metallic film provided with openings may be formed around the outer circumference of the optical fiber **20**.

[0151] One feature of the manufacturing method of the optical device **4** is that the first metallic film formed on the V-shaped groove of the substrate, with the openings formed in a periodically repeating fashion, and the flat-patterned second metallic film formed on the outer circumference of the optical fiber are bonded together by surface activated bonding.

[0152] FIG. **15** is a diagram showing a further alternative optical device **5**. In FIG. **15**, the same component elements as those in FIG. **1** are designated by the same reference numerals, and the description of such component elements will not he repeated.

[0153] In FIG. **15**, the V-shaped groove **11** of a prescribed size is formed in the surface of the silicon substrate **10**, and a metallic film provided with micro-bumps **19** is formed on the surface of the V-shaped groove **11**. The material of the micro-bumps is Au. The micro-bumps **19** will be described in detail later.

[0154] As in the optical device **1**, the outer circumference of the optical fiber **20** is covered with the flat-patterned second metallic film **24**. The material of the second metallic film **24** is Au.

[0155] The optical fiber **20** is fitted into the V-shaped groove **11** of the silicon substrate **10** and pressed thereon under a prescribed load. Thereupon, the micro-bumps **19** formed on the surface of the V-shaped groove **11** and the second metallic film **24** formed on the outer circumference of the optical fiber **20** are bonded together by surface activated bonding, and the optical fiber **20** is thus bonded fixedly to the silicon substrate **10**.

[0156] The micro-bumps **19** are formed by dry-etching or wet-etching an Au film formed by sputtering on the surface of the V-shaped groove **11**. The micro-bumps **19** are cylindrically shaped protrusions, each with a height of 2 μm and a diameter of 5 μm, and are arranged with uniform spacing at a pitch of 10 to 25 μm in the lateral and longitudinal directions. The shape, height, width, pitch, etc., of the micro-bumps are only examples, and are not limited to those described above. Since the micro-bumps **19** are formed by etching the Au flim formed by sputtering, the heights of the micro-bumps **19** are precisely egual across the entire area.

[0157] The only difference between the manufacturing method of the optical device **5** shown in FIG. **15** and the manufacturing method of the optical device **1** earlier described is that, in the optical device **5**, the micro-bumps **19** are formed by etching after forming the first metallic film **12** on the surface of the V-shaped groove **11** (see S4 in FIG. **4**). Compared with the flat-patterned first metallic film **12**, the micro-bumps **19** are easier to compress under pressure, and hence the control is easy when positioning the optical fiber **20**.

[0158] FIG. **16** is a diagram showing a further alternative optical device **6**. In FIG. **16**, the same component elements as those in FIG. **1** are designated by the same reference numerals, and the description of such component elements will not be repeated.

[0159] The difference between the optical device **6** shown in FIG. **16** and the optical device **1** shown in FIG. **1** is that, in the optical device **6**, the gap created between the V-shaped groove **11** and the optical fiber **20** is filled with a bonding resin **60**.

[0160] In FIG. **16**, the V-shaped groove **11** of a prescribed size is formed in the surface of the silicon substrate **10**, and the first metallic film **12** is formed on the surface of the V-shaped groove **11**. The material of the first metallic film **12** is Au. As in the optical device **1**, the outer circumference of the optical fiber **20** is covered with the flat-patterned second metallic film **24**. The material of the second metallic film **24** is Au.

[0161] The optical fiber **20** is fitted into the V-shaped groove **11** of the silicon substrate **10** and pressed thereon under a prescribed load. Thereupon, the first metallic film **12** formed on the surface of the V-shaped groove **11** and the second metallic film **24** formed on the outer circumference of the optical fiber **20** are bonded together by surface activated bonding, and the optical fiber **20** is thus bonded fixedly to the silicon substrate **10**.

[0162] The only difference between the manufacturing method of the optical device **6** shown in FIG. **16** and the manufacturing method of the optical device **1** earlier described is that, in the optical device **6**, the step for filling the bonding resin **60** into the gap created between the V-shaped groove **11** and the optical fiber **20** is added after fixedly bonding the optical fiber **20** to the silicon substrate **10**. Since the optical fiber **20** is bonded to the silicon substrate **10** by surface activated bonding, the position of the optical fiber **20** relative to the optical fiber **10** is unaffected even when the bonding resin **60** is caused to contract or expand under the effect of heat, etc. Furthermore, in the optical device **6**, the optical fiber **20** can be fixedly bonded to the silicon substrate **10** in a more secure manner by the bonding resin **60**. In the fabrication of the optical device **6**, the optical fiber **20** may be fixedly bonded to the silicon substrate **10** in accordance with any one of the manufacturing methods described in connection with the optical devices **2** to **7**.

[0163] FIG. **17** is a diagram showing a further alternative optical device **7**. In FIG. **17**, the same component elements as those in FIG. **1** are designated by the same reference numerals, and the description of such component elements will not be repeated here.

[0164] The difference between the optical device **6** shown in FIG. **17** and the optical device **5** shown in FIG. **15** is that the optical device **7** does not include the V-shaped groove **11** but instead includes a reinforcing resin **70**.

[0165] In FIG. **17**, micro-bumps **19** are formed as a datum plane surface on the surface of the silicon substrate **10**. The material of the micro-bumps **19** is Au. The geometry and the method of fabrication of the micro-bumps **19** are the same as those described for the optical device **5**.

[0166] As in the optical device **1**, the outer circumference of the optical fiber **20** is covered with the flat-patterned second metallic film **24**. The material of the second metallic film **24** is Au.

[0167] The optical fiber **20** is placed in a designated position on the silicon substrate **10**, and pressed thereon under a prescribed load. Thereupon, the micro-bumps **19** formed on the silicon substrate **10** and the second metallic film **24** formed on the outer circumference of the optical fiber **20** are bonded together by surface activated bonding, and the optical fiber **20** is thus bonded fixedly to the silicon substrate **10**.

[0168] The manufacturing method of the optical device **7** shown in FIG. **17** differs from the manufacturing method of the optical device **5** earlier described, in that the V-shaped groove **11** is not formed but instead the micro-bumps **19** are formed on the datum plane surface of the substrate **10**, and in that the manufacturing method includes a step for fixing (or reinforcing) the optical fiber **20** with the reinforcing resin **70** after fixedly bonding the optical fiber **20** to the silicon substrate **10**.

[0169] Compared with the flat-patterned first metallic film **12** of the optical device **1**, the micro-bumps **19** are easier to compress under pressure, and hence the control (adjustment) in the height direction (Z-axis direction in the figure) relative to the silicon substrate **10** is easy when positioning the optical fiber **20**, as in the case of the optical device **5**.

[0170] Since the optical device **7** shown in FIG. **17** does not include the V-shaped groove **11**, the position of the optical fiber **20** on the silicon substrate **10** can also be adjusted in the lateral direction (X-axis direction in the figure) by moving the optical fiber **20**. This adjustment can be made because there is space in the lateral direction of the optical fiber **20**. Furthermore, since the heights of all the micro-bumps **19** can be aligned precisely by reference to the datum plane surface of the substrate **10**, the adjustment in the height direction can be made more precisely than in the case of the V-shaped groove.

[0171] In the optical device **7** shown in FIG. **17**, the micro-bumps **19** are formed on the datum plane surface of the substrate **10**, but instead of the micro-bumps **19**, the first metallic film **13** having the stripe-shaped raised and recessed portions, such as shown in the optical device **2**, or the first metallic film **14** having the openings **14***a*, such as shown in the optical device **4**, may be formed on the datum plane surface of the substrate **10**. Even when the first metallic film **13** having the stripe-shaped raised and recessed portions or the first metallic film **14** having the openings **14***a* is formed on the datum plane surface, there is space in the lateral direction of the optical fiber **20**. It is therefore possible to control (adjust) the position of the optical fiber **20** on the silicon substrate **10** in the lateral direction (X-axis direction in the figure).

[0172] FIG. **18** is a perspective view showing a further alternative optical device **100**.

[0173] The optical device **100** is manufactured by fixedly bonding the optical fiber **20** to the silicon substrate **10** in accordance with the manufacturing method described for the optical device **2**. Alternatively, the optical device **100** may be manufactured by fixedly bonding the optical fiber **20** to the silicon substrate **10** in accordance with any one of the manufacturing methods described for the optical devices **1** and **3** to **7**.

[0174] In the optical device **100**, the same component elements as those in the optical device **2** are designated by the same reference numerals, and the description of such component elements will not be repeated. The optical device **100** includes a semiconductor laser **50** in addition to the silicon substrate **10** and the optical fiber **20** fixedly bonded to the silicon substrate **10**.

[0175] The semiconductor laser **50** is fixedly bonded to the silicon substrate **10** via micro-buxos or the like (not shown). The first metallic film **13** formed on the V-shaped groove **11** and the second metallic film **24** formed on the outer circumference of the optical fiber **20** are bonded together by surface activated bonding, and the la optical fiber **20** is thus bonded fixedly to the silicon substrate **10**.

[0176] It is extremely important to fixedly bond the optical fiber **20** by aligning the optical axis **26** of the optical fiber **20** with the optical axis **51** of the laser light that the semiconductor laser **50** outputs. The optical fiber **20** is fitted into the V-shaped groove **11**, and its position in both horizontal directions (X-axis and Y-axis directions) relative to the silicon substrate **10** is fixed. On the other hand, the height (in the Z-axis direction) of the optical fiber **20** can be adjusted by varying the bonding load and thereby adjusting the amount of compression of the raised portions **13***a* of the first metallic film **13** (see FIG. **10**).

[0177] Accordingly, in the optical device **100**, a precise optical axis alignment between the optical elements (semiconductor laser **50** and optical device **20**) mounted on the silicon substrate **10** can be accomplished by adjusting the load. It is thus possible to manufacture a high-performance optical device that achieves optimum optical coupling.

[0178] Though not shown in FIG. **18**, metallic films, interconnection patterns, etc., for bonding other optical elements can also be formed efficiently on the surface of the silicon substrate **10** simultaneously with the formation of the first metallic film **13** on the surface of the V-shaped groove **11** of the silicon substrate **10**. It is thus possible to easily achieve an optical device in which a plurality of optical elements are integrated efficiently on a silicon substrate.

[0179] The optical device and the optical device manufacturing method described above can be widely applied in a variety of fields such as laser projectors, laser light illumination equipment, optical tweezers, and the like.

1-15. (canceled)

16. A method for manufacturing an optical device with an optical fiber mounted on a substrate, comprising the steps of:

forming micro-bumps on a portion of said substrate;

forming a metallic film on a portion of an outer circumference of said optical fiber;

bonding together with micro-bumps and said metallic film by surface activated bonding at normal temperature without heating for bonding; and

adjusting the position of an optical axis of said optical fiber by compressing said micro-bumps.

17. The optical device manufacturing method according to claim **16**, further comprising the step of forming a V-shaped groove in said surface, and

wherein said microbumps are formed on said V-shaped groove.

18. The optical device manufacturing method according to claim **16**, further comprising the step of fixing said optical fiber onto said first metallic film by using a reinforcing resin.

19. The optical device manufacturing method according to claim **16**, wherein said micro-bumps are formed of Au.

20. The optical device manufacturing method according to claim **16**, further comprising the steps of:

bonding a light emitting device on said substrate; and

adjusting the position between said optical axis of said optical fiber and an optical axis of an emitted light from said light emitting device by compressing said micro-bumps.

21. The optical device manufacturing method according to claim **16**, wherein second micro-bumps formed on said substrate and said light emitting device are bonded together by surface activated bonding at normal temperature without heating for bonding.

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