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Kameshima

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(54) RADIATION DETECTING ELEMENT, RADIATION DETECTING APPARATUS AND MANUFACTURING METHOD OF RADIATION DETECTING ELEMENT

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G21K 4/00 (2006.01)

(52) **U.S. Cl.**
CPC ***G01T 1/20*** (2013.01); *G21K 2004/08* (2013.01); *G21K 2004/12* (2013.01)

(58) **Field of Classification Search**
CPC ... G01T 1/20; G21K 2004/08; G21K 2004/12
See application file for complete search history.

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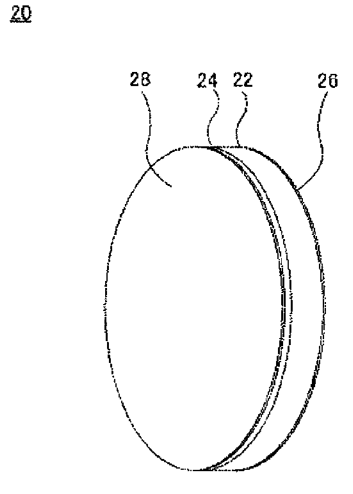
Primary Examiner — Christine Sung

(57) ABSTRACT

When a scintillator and a reinforcing member are bonded by using an adhesive, scattering and reflection occur at interfaces between the scintillator and the adhesive and between the adhesive and the reinforcing member. Due to this, a blurred image is formed on a sensor, and the resolution deteriorates. A radiation detecting element comprises: a substrate transparent to visible light; and a fluorescent screen that emits fluorescence in response to radiation by a dopant added to a material that is the same as a material of the substrate, wherein the fluorescent screen is thinner than the substrate, and the substrate and the fluorescent screen are bonded while maintaining continuity of a refractive index.

4 Claims, 5 Drawing Sheets



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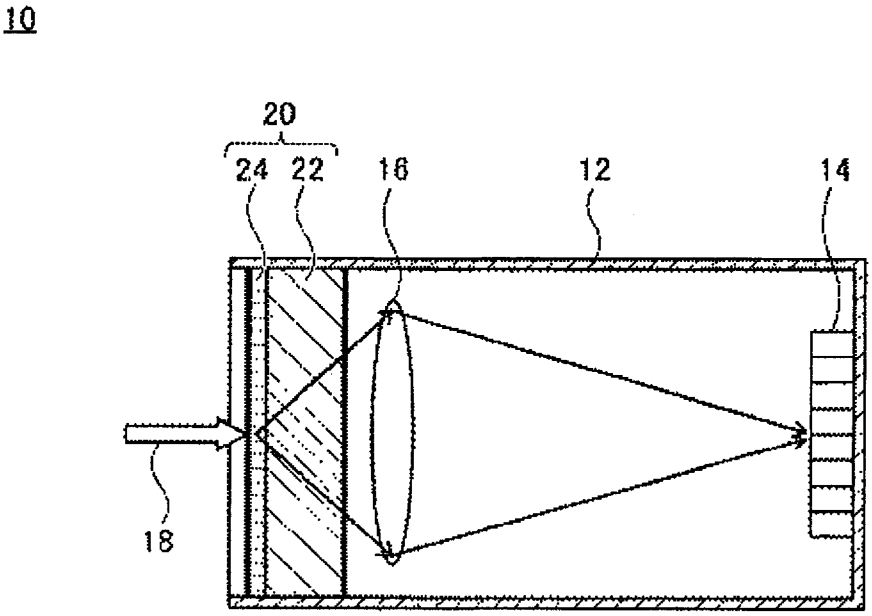


FIG. 1

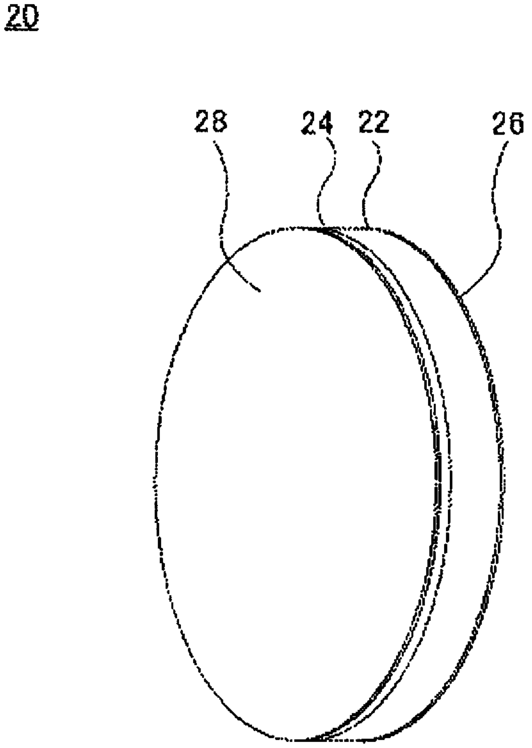


FIG. 2

FIG. 3A

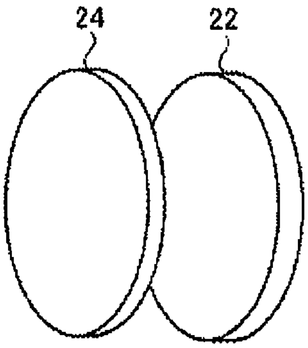


FIG. 3B

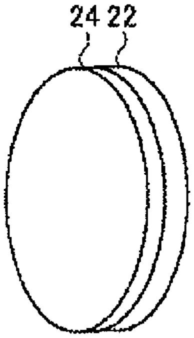


FIG. 3C

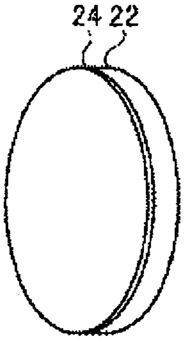
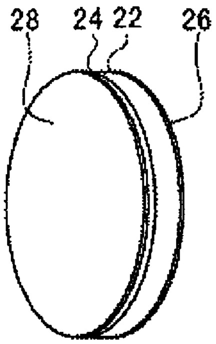


FIG. 3D



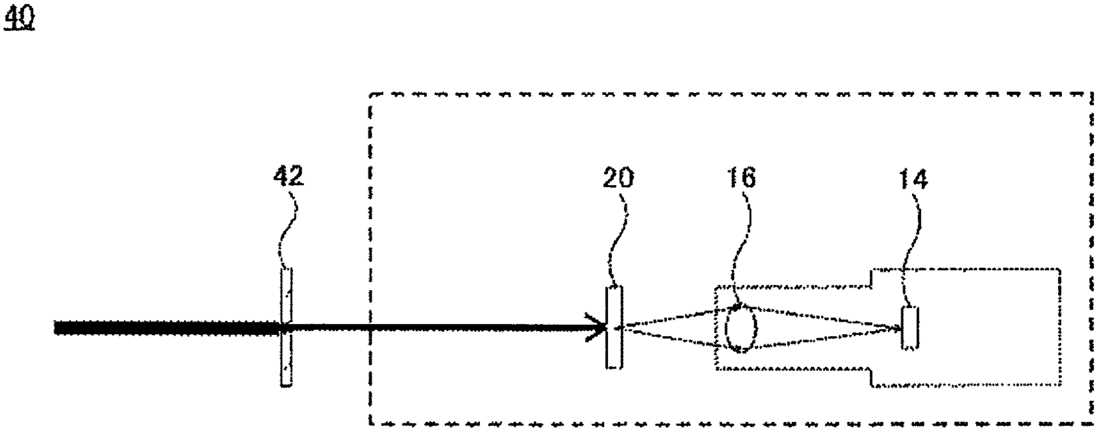

40
42
20
16
14

FIG. 4

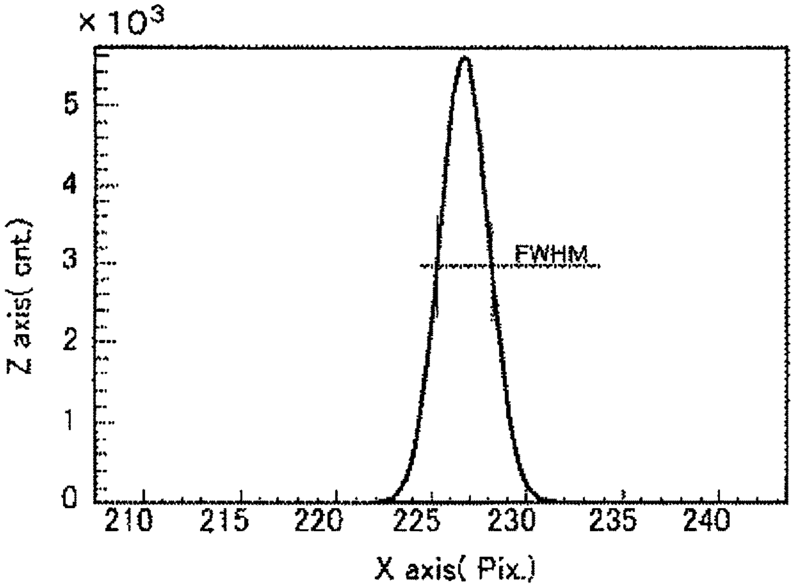

× 10³
5
4
3
2
1
0
Z axis(cnt.)
FWHM
210
215
220
225
230
235
240
X axis(Pix.)

FIG. 5

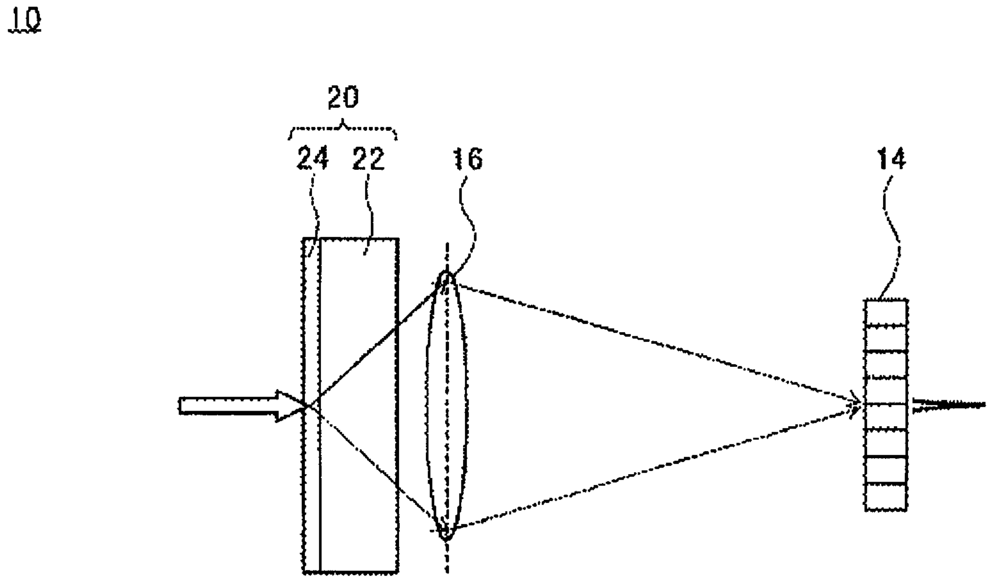


FIG. 6

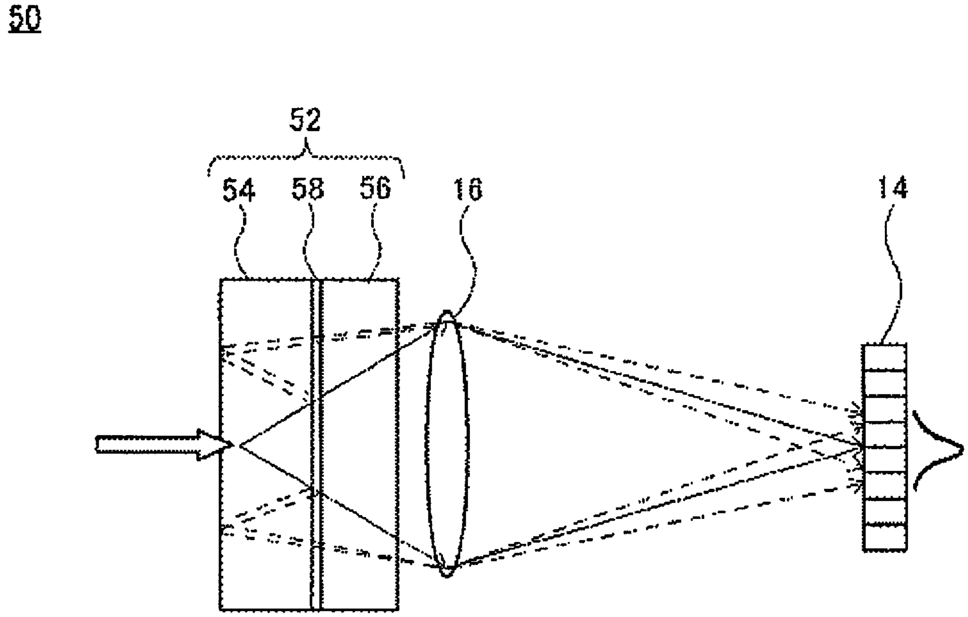


FIG. 7

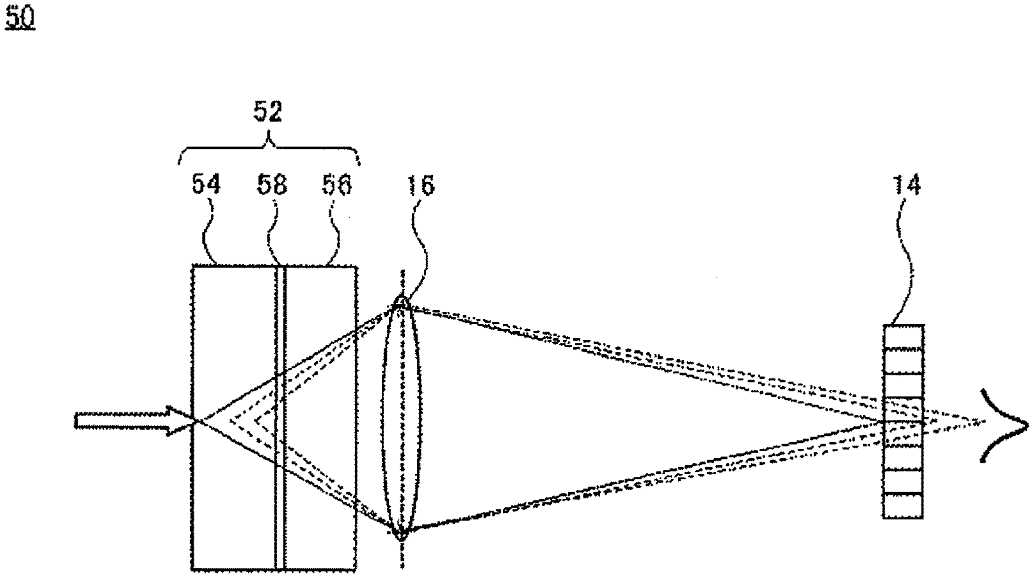


FIG. 8

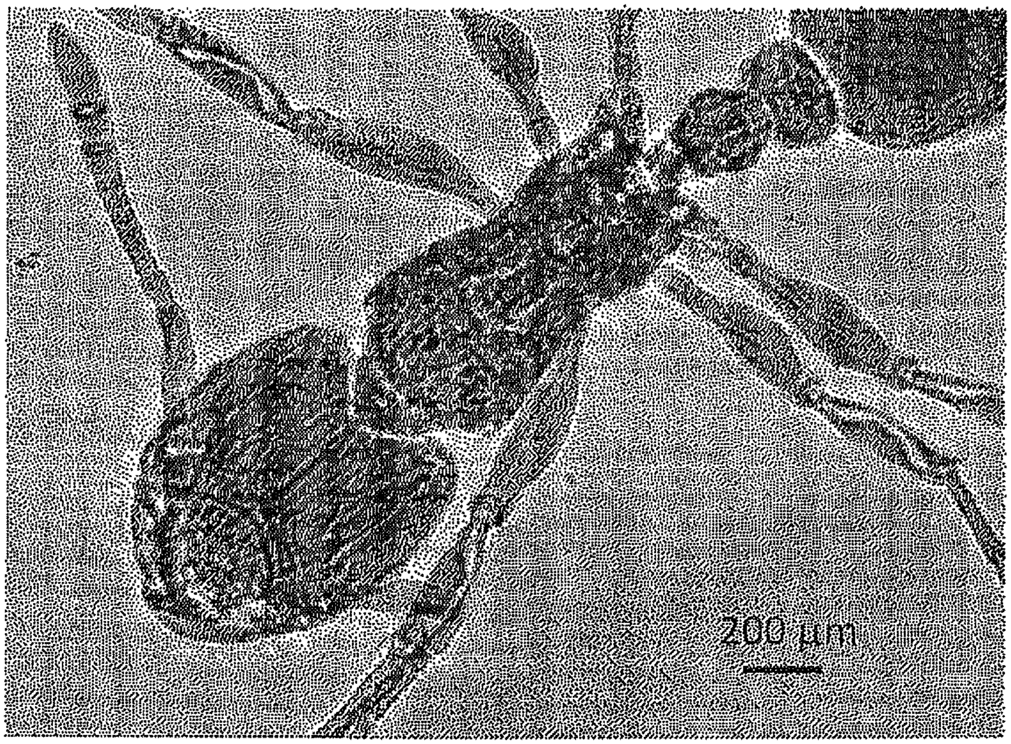


FIG. 9

RADIATION DETECTING ELEMENT, RADIATION DETECTING APPARATUS AND MANUFACTURING METHOD OF RADIATION DETECTING ELEMENT

The contents of the following Japanese patent application are incorporated herein by reference:

No. 2014-172299 filed on Aug. 27, 2014.

BACKGROUND

1. Technical Field

The present invention relates to a radiation detecting element, a radiation detecting apparatus, and a manufacturing method of a radiation detecting element.

2. Related Art

It has been known that a scintillator of a measuring apparatus to measure radiation is made thin while maintaining the strength of the scintillator by bonding the scintillator and a transparent reinforcing member with an adhesive to make them thin, as described for example in Japanese Patent Application Publication No. 2012-26821.

However, when a scintillator and a reinforcing member are bonded by using an adhesive, scattering and reflection occur at interfaces between the scintillator and the adhesive and between the adhesive and the reinforcing member. Due to this, a blurred image is formed on a sensor, and the resolution deteriorates.

SUMMARY

According to a first aspect of the present invention, a radiation detecting element comprises: a substrate transparent to visible light; and a fluorescent screen that emits fluorescence in response to radiation by a dopant added to a material that is the same as a material of the substrate, wherein the fluorescent screen is thinner than the substrate, and the substrate and the fluorescent screen are bonded while maintaining continuity of a refractive index.

According to a second aspect of the present invention, a radiation detecting apparatus comprises: a radiation detecting element having a substrate transparent to visible light, and a fluorescent screen that emits fluorescence in response to radiation by a dopant added to a material that is the same as a material of the substrate, wherein the fluorescent screen is thinner than the substrate, and the substrate and the fluorescent screen are bonded while maintaining continuity of a refractive index; an imaging optical system that forms an image of fluorescence emitted by the fluorescent screen; and a photoelectric conversion element on which photoelectric conversion pixels that perform photoelectric conversion on fluorescence an image of which has been formed are disposed two-dimensionally.

According to a third aspect of the present invention, a manufacturing method of a radiation detecting element comprises: bonding, by solid state diffusion, a substrate transparent to visible light and a fluorescent screen that emits fluorescence in response to radiation by a dopant added to a material that is the same as a material of the substrate; and thinning the fluorescent screen.

The summary clause does not necessarily describe all necessary features of the embodiments of the present invention. The present invention may also be a sub-combination of the features described above.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic cross-sectional view of a radiation detecting apparatus **10**.

FIG. **2** is a schematic perspective view of a radiation detecting element **20**.

FIGS. **3**A to **3**D are figures for explaining a manufacturing method of the radiation detecting element **20**.

FIG. **4** is a schematic cross-sectional view of a spatial resolution measuring apparatus **40**.

FIG. **5** shows a profile of a point spread function of fluorescence acquired from a CCD sensor **14**.

FIG. **6** is a schematic diagram of a part that detects radiation in the radiation detecting apparatus **10**.

FIG. **7** is a schematic diagram of a part that detects radiation in a radiation detecting apparatus **50** which is a comparative example.

FIG. **8** is a schematic diagram for explaining a light-emission position of fluorescence in the radiation detecting apparatus **50** in FIG. **7**.

FIG. **9** shows an example of an image captured with the radiation detecting apparatus **10**.

DESCRIPTION OF EXEMPLARY EMBODIMENTS

Hereinafter, (some) embodiment(s) of the present invention will be described. The embodiment(s) do(es) not limit the invention according to the claims, and all the combinations of the features described in the embodiment(s) are not necessarily essential to means provided by aspects of the invention.

FIG. **1** is a schematic cross-sectional view of a radiation detecting apparatus **10**. The radiation detecting apparatus **10** is an indirect conversion-type two-dimensional radiation detector to measure a two-dimensional signal of a high energy radiation such as an X-ray by converting it into low energy fluorescence. One example of radiation is an X-ray free electron laser (hereinafter, called an XFEL in some cases). The radiation detecting apparatus **10** has a cylindrical housing **12**, a CCD sensor **14**, an objective lens **16** and a radiation detecting element **20**.

The radiation detecting element **20** is circular plate-like, and is disposed on one end surface side of the housing **12**. The radiation detecting element **20** contains a fluorescent substance, and converts a high energy radiation that enters from the direction indicated with an arrow **18** into numerous low energy fluorescence lines. The radiation detecting element **20** makes detection by the CCD sensor **14** possible by converting radiation at a frequency that is outside the region of sensitivity and therefore cannot be detected by the CCD sensor **14** into fluorescence at a frequency that is within the region of sensitivity. It should be noted that the shape of the radiation detecting element **20** is not limited to a circle, but may be any shape such as a square.

The CCD sensor **14** has photoelectric conversion pixels that are disposed two-dimensionally. The CCD sensor **14** converts light in the region of sensitivity including visible light the image of which has been formed by the objective lens **16** into an electrical signal and outputs it. The CCD sensor **14** is disposed on another end surface side of the housing **12** so that the surface on which the photoelectric conversion pixels are disposed faces the radiation detecting element **20**. The CCD sensor **14** is one example of a photoelectric conversion element, and an EMCCD sensor or a CMOS sensor may be used in place of the CCD sensor **14**. Because in an EMCCD sensor, a function of multiplying electrons is added to a readout unit of the CCD sensor, faint light can be measured highly sensitively by using the EMCCD sensor. Because a CMOS sensor adopts a highspeed readout system, light can be measured at a high frame rate by using the CMOS sensor.

The objective lens **16** is disposed between the radiation detecting element **20** and the CCD sensor **14** so that the objective lens **16**, the radiation detecting element **20** and the CCD sensor **14** are on a straight line. Furthermore, preferably, the CCD sensor **14**, the radiation detecting element **20** and the objective lens **16** are disposed so that the center of the surface of the CCD sensor **14** on which the photoelectric conversion pixels are disposed and the center of the radiation detecting element **20** match the optical center of the objective lens **16**.

The objective lens **16** forms an image of fluorescence emitted from the radiation detecting element **20** on the surface of the CCD sensor **14** on which the photoelectric conversion pixels are disposed. The objective lens **16** may be configured with a single lens, or may be configured with a plurality of lenses including an objective lens and an imaging lens. It should be noted that the objective lens **16** is one example of an imaging optical system.

FIG. **2** is a schematic perspective view of the radiation detecting element **20**. The radiation detecting element **20** has a substrate **22**, a fluorescent screen **24** and anti-reflection films **26**, **28**.

The substrate **22** is disposed on the objective lens **16** side of the radiation detecting element **20**. The transmittance of fluorescence which is visible light for the substrate **22** is higher and the fluorescence is more transparent than radiation whereas the transmittance of radiation for the substrate **22** is lower than visible light. The substrate **22** is configured by $Y_3Al_5O_{12}$ (hereinafter, called YAG). It should be noted that YAG is one example of a material to configure a substrate, and any other materials including Lu_2SiO_5, $LuYSiO_5$, $LuYSiO_5$, $Gd_3Ga_5O_{12}$, $CdWO_4$, $Bi_4Ge_3O_{12}$, Gd_2SiO_5, Gd_2O_2S, Y_2SiO_5, Yb_2SiO_5, $LuAlO_3$, $Lu_3Al_5O_{12}$, $Gd_3Al_2Ga_3O_{12}$, $Lu_{0.7}Y_{0.3}AlO_3$, or a mixture thereof may be used.

The fluorescent screen **24** is disposed on a side of the radiation detecting element **20** where radiation enters. The fluorescent screen **24** emits fluorescence corresponding to radiation by adding a dopant, Ce, to YAG which is a material same as the material of the substrate **22**. That is, the fluorescent screen **24** functions as a scintillator that emits fluorescence corresponding to radiation that has entered there. It should be noted that, in the present embodiment, YAG to which Ce has been added emits fluorescence whose wavelength centers at 550 nm. Also, Ce is one example of a dopant to be added to the fluorescent screen **24**, and as other dopants, Mn, Tl, Sn, Pb, Eu, Tb, La, Gd, Al, Ge, Yb, Nd, Sm, Er, Tm, Am or Pr may be used.

The thickness of the substrate **22** needs to have the proportion so that while the handling strength is maintained, radiation that is transmitted through the fluorescent screen **24** gets attenuated and extinguished. Also, in order to suppress spherical aberration occurring in the substrate **22**, it is preferred to make the thickness of the substrate **22** thin. In the present embodiment, the thickness of the substrate **22** is 3 mm for example.

On the other hand, the thickness of the fluorescent screen **24** is smaller than the thickness of the substrate **22**, and is preferably within the range of 1 μm to 2 mm. In the present embodiment, the thickness of the fluorescent screen **24** is 20 μm for example. By making the fluorescent screen **24** thin, scattering of light-emission points of fluorescence in the traveling direction of radiation can be prevented; as a result, the spatial resolution of the radiation detecting apparatus **10** improves. However, the spatial resolution of the radiation detecting apparatus **10** does not improve to be equal to or exceed the resolution that is determined by the diffraction limit determined by fluorescence wavelength and the numerical aperture of the objective lens **16** and the pixel size and optical magnification of the CCD sensor **14**. For this reason, in a case where the highest spatial resolution of the radiation detecting apparatus **10** is to be obtained, preferably, the objective lens **16** having high optical magnification so that the pixel size of the CCD sensor **14** becomes smaller than the diffraction limit size of fluorescence is used, and the thickness of the fluorescent screen **24** is selected so that it becomes the depth of focus determined by the diffraction limit of fluorescence. Furthermore, the thickness of the fluorescent screen **24** is determined considering that the target viewing field, spatial resolution, and amount of emitted light of fluorescence can be ensured, and that a region to which a fluorescent substance, Ce, is added can be ensured on the entire surface of the fluorescent screen **24** even when the fluorescent screen **24** is bonded with the substrate **22** by solid state diffusion.

The fluorescent screen **24** and the substrate **22** are bonded while maintaining continuity of the refractive index. Here, bonding while maintaining continuity of the refractive index means that the refractive index structure of an interface where the fluorescent screen **24** and the substrate **22** are bonded is substantially uniform. For example, when the difference between the refractive index of the substrate **22** configured by YAG and the refractive index of the fluorescent screen **24** in which Ce is added to YAG is on the order of 0.1%, and the substrate **22** and the fluorescent screen **24** are bonded, the refractive index structure of the bonding interface can be said to be uniform. By making the refractive index structure of the interface where the fluorescent screen **24** and the substrate **22** are bonded substantially uniform, scattering, refraction and reflection of fluorescence at the bonding interface can be prevented.

The anti-reflection film **26** and the anti-reflection film **28** are disposed on both end faces of the bonded substrate **22** and fluorescent screen **24**, respectively. The anti-reflection film **26** is disposed on a surface of the substrate **22** that is opposite to the surface of the substrate **22** that is bonded with the fluorescent screen **24**. The anti-reflection film **26** prevents reflection of fluorescence emitted from the fluorescent screen **24**. The anti-reflection film **26** is a thin film having the thickness equivalent to ¼ of the wavelength of fluorescence for example. In the present embodiment, because the wavelength of fluorescence of YAG to which Ce is added is 550 nm, the anti-reflection film **26** is a thin film of 137.5-nm thickness which is equivalent to ¼ of 550 nm. The anti-reflection film **26** prevents reflection of fluorescence by cancelling out light reflected on the interface between the substrate **22** and the anti-reflection film **26** by means of light reflected on the front surface of the anti-reflection film **26**. Also, a multi-layered film on which two or more layers of dielectric films are coated may be used as the anti-reflection film **26**.

The anti-reflection film **28** is disposed on a surface of the fluorescent screen **24** that is opposite to the surface of the fluorescent screen **24** that is bonded with the substrate **22**. The anti-reflection film **28** prevents reflection of fluorescence emitted from the fluorescent screen **24** and re-reflection of reflected light of fluorescence that occurs on the surface of the substrate **22** that is opposite to the surface of the substrate **22** that is bonded with the fluorescent screen **24**. It should be noted that because the configuration of the anti-reflection film **28** is the same as that of the anti-reflection film **26**, explanation of the configuration of the anti-reflection film **28** is omitted.

FIGS. **3**A to **3**D are figures for explaining a manufacturing method of the radiation detecting element **20**. FIG. **3**A shows a step where the substrate **22** and the fluorescent screen **24** are prepared for respectively. In this state, for example, the thickness of the substrate **22** is 3 mm, and the thickness of the fluorescent screen **24** is 1 mm. It should be noted that the thicknesses of the substrate **22** and the fluorescent screen **24** before bonding may be determined as appropriate considering easiness of handling or the like.

FIG. **3**B shows a step where the substrate **22** and the fluorescent screen **24** are bonded by solid state diffusion. The bonding surface of the substrate **22** is superposed on the bonding surface of the fluorescent screen **24**, and bonded by solid state diffusion. It should be noted that, before superposing the substrate **22** and the fluorescent screen **24**, the surface of the substrate **22** on which it is bonded with the fluorescent screen **24** may be polished and smoothed. Similarly, the surface of the fluorescent screen **24** on which it is bonded with the substrate **22** may be polished and smoothed. By smoothing the bonding surfaces, the contact area of the substrate **22** and the fluorescent screen **24** can be increased. Thereby, the reliability of solid state diffusion bonding can be improved.

Also, before superposing the substrate **22** and the fluorescent screen **24**, the surface of the substrate **22** on which it is bonded with the fluorescent screen **24** may be washed. Similarly, the surface of the fluorescent screen **24** on which it is bonded with the substrate **22** may be washed. In solid state diffusion bonding, if the bonding surfaces of the substrate **22** and the fluorescent screen **24** are contaminated, diffusion of respective atoms does not proceed on the contaminated part, and the bonding strength of solid state diffusion bonding becomes low. By washing the bonding surfaces, contamination can be removed, thereby improving the reliability of solid state diffusion bonding.

Also, in solid state diffusion bonding, pressure may be applied in the bonding directions of the substrate **22** and the fluorescent screen **24**, respectively. By applying pressure in the bonding directions of the substrate **22** and the fluorescent screen **24**, the interfaces of the substrate **22** and the fluorescent screen **24** can be closely adhered to each other. Thereby, the reliability of solid state diffusion bonding can be improved.

Furthermore, in solid state diffusion bonding, the substrate **22** and the fluorescent screen **24** may be heated. By heating the substrate **22** and the fluorescent screen **24**, diffusion of atoms of the substrate **22** and atoms of the fluorescent screen **24** at the bonding surfaces is enhanced. Thereby, the bonding strength of solid state diffusion bonding can be improved.

FIG. **3**C shows a state where the fluorescent screen **24** is polished and thinned. The fluorescent screen **24** is polished and thinned from a surface on a side on which the substrate **22** is not bonded. It should be noted that polishing is performed for example by chemical mechanical polishing (hereinafter, called CMP in some cases), and the fluorescent screen **24** of 1-mm thickness is thinned to 20 μm. It should be noted that the thickness of the fluorescent screen **24** may be 4 μm, 2 μm, or 1 μm. Also, polishing may be mechanical polishing such as machining. Because the fluorescent screen **24** is reinforced by being bonded with the substrate **22** of 3-mm thickness, the fluorescent screen **24** can be thinned to the thickness of 1 μm without damaging the fluorescent screen **24**. Also, in this manner, by thinning the fluorescent screen **24** from the side where radiation enters by CMP, the surface of the fluorescent screen **24** on the side where radiation enters can be flattened highly accurately.

FIG. **3**D shows a step where the anti-reflection film **26** and the anti-reflection film **28** are provided to both end faces of the bonded fluorescent screen **24** and substrate **22**. As described above, the anti-reflection film **26** is disposed on the side surface of the substrate **22** on the surface of the side on which the fluorescent screen **24** is not provided. Also, the anti-reflection film **28** is disposed on the side surface of the fluorescent screen **24** on the surface of the side on which the substrate **22** is not provided. The anti-reflection film **26** and the anti-reflection film **28** are disposed on the respective surfaces for example due to vacuum deposition.

FIG. **4** is a schematic cross-sectional view of a spatial resolution measuring apparatus **40**. The spatial resolution of the radiation detecting element **20** according to the present embodiment is explained by using FIG. **4**. The spatial resolution measuring apparatus **40** has a pinhole plate **42** to which a ϕ10-μm pinhole is provided, the radiation detecting element **20**, the objective lens **16** and the CCD sensor **14**. It should be noted that in FIG. **4**, elements that are the same as those shown in FIG. **1** are provided with the same reference numerals, and overlapping explanation is omitted.

For measurement of the spatial resolution, first, an XFEL was allowed to pass through the ϕ10 μm pinhole provided to the pinhole plate **42**. Thereby, the XFEL that entered the radiation detecting element **20** was cut into ϕ10 μm.

Next, the XFEL cut into ϕ10 μm was entered into the radiation detecting element **20**, and fluorescence was emitted. An image of the fluorescence emitted from the radiation detecting element **20** was formed in the CCD sensor **14** by using the objective lens **16**. Thereby, the profile of a point spread function of the fluorescence the image of which was formed by the objective lens **16** was acquired from the CCD sensor **14**.

Next, the profile of a point spread function of the XFEL cut into ϕ10 μm at the position of the radiation detecting element **20** was acquired. Then, the profile of the point spread function of the XFEL cut into ϕ10 μm at the position of the radiation detecting element **20** was deconvoluted from the profile of the point spread function acquired from the CCD sensor **14**, and thus the spatial resolution of the optical system configured by the radiation detecting element **20** and the objective lens **16** was calculated.

FIG. **5** shows the profile of the point spread function of fluorescence acquired from the CCD sensor **14**. The vertical axis in FIG. **5** indicates the numbers of counts of received fluorescence, and the horizontal axis indicates pixel positions where the received fluorescence was received. The half-value width calculated from the profile of the point spread function acquired from the CCD sensor **14** was 12 μm. The half-value width calculated from the profile of the point spread function the XFEL cut into ϕ10 μm at the position of the radiation detecting element **20** was 9 μm.

Here, the profile of the point spread function acquired from the CCD sensor **14** is assumed to be A and its half-value width is assumed to be a. Also, the profile of the point spread function of the XFEL cut into ϕ10 μm at the position of the radiation detecting element **20** is assumed to be B, and its half-value width is assumed to be b. Also, the profile of the point spread function from the radiation detecting element **20** to the CCD sensor **14** is assumed to be C, and its half-value width is assumed to be c. Then, because the profile A is a profile obtained by convolution of the profile B and the profile C, the following relational expression (1) is established when these profiles are deconvoluted and they are respectively expressed with the half-value widths of the profiles.

$$a=[(b)^2+(c)^2]^{1/2} \quad (1)$$

By using the relational expression (1) and substituting **12** for a and 9 for b to calculate the half-value width c, the half-value width c=7.9 is obtained. Thereby, it can be known that the spatial resolution from the radiation detecting element **20** to the CCD sensor **14** is about 8 μm in terms of a half-value width.

Also, even when measurement of spatial resolution was performed for about six hours by using the spatial resolution measuring apparatus **40**, there was no malfunction of the CCD sensor **14**. This indicates that the XFEL was attenuated by the substrate **22** and the XFEL did not reach the CCD sensor **14**. It should be noted that if an XFEL reaches the CCD sensor **14**, malfunction that the XFEL destroys the photoelectric conversion elements and the operation of the CCD sensor **14** stops or dark current of the CCD sensor **14** increases and noise increases occurs.

FIG. **6** is a schematic diagram of a part that detects radiation in the radiation detecting apparatus **10**. Effects of the radiation detecting apparatus **10** and the radiation detecting element **20** according to the present embodiment are explained by using FIG. **6**. It should be noted that in FIG. **6**, elements that are the same as those shown in FIG. **1** are provided with the same reference numerals, and overlapping explanation is omitted.

In the present embodiment, the substrate **22** and the fluorescent screen **24** in the radiation detecting element **20** are configured by the same material, YAG. Furthermore, because the substrate **22** and the fluorescent screen **24** are bonded while maintaining continuity of the refractive index, fluorescence emitted from the fluorescent screen **24** is not refracted at the interface between the substrate **22** and the fluorescent screen **24**. If it is supposed that fluorescence is refracted at the interface between the substrate **22** and the fluorescent screen **24**, the refracted fluorescence is not focused on the CCD sensor **14** by the objective lens **16** due to the influence of spherical aberration. Accordingly, by bonding the interface between the substrate **22** and the fluorescent screen **24** while maintaining continuity of the refractive index, refraction of fluorescence at the bonding interface can be prevented, thereby improving resolution of an image formed on the CCD sensor **14** by the objective lens **16**.

Also, by bonding the substrate **22** and the fluorescent screen **24** while maintaining continuity of the refractive index, fluorescence emitted from the fluorescent screen **24** can also be prevented from being reflected at the bonding interface between the fluorescent screen **24** and the substrate **22**. If fluorescence is reflected at the interface, the light amount of an image formed on the CCD sensor **14** by the objective lens **16** decreases. Accordingly, the light amount of an image formed on the CCD sensor **14** can be increased by suppressing reflection at the interface, and the sensitivity of the radiation detecting apparatus **10** can be increased.

Also, if fluorescence is reflected at the bonding interface between the fluorescent screen **24** and the substrate **22**, the resolution of the radiation detecting apparatus deteriorates. Deterioration of the resolution of the radiation detecting apparatus due to the reflection is explained by using FIG. **7**.

FIG. **7** is a schematic diagram of a part that detects radiation in a radiation detecting apparatus **50** according to a comparative example. The radiation detecting apparatus **50** has a radiation detecting element **52**, the objective lens **16** and the CCD sensor **14**. Also, the radiation detecting element **52** is configured by bonding a fluorescent screen **54** and a substrate **56** by an adhesive **58**. Differences between the radiation detecting apparatus **50** and the radiation detecting apparatus **10** shown in FIG. **1** are that the radiation detecting element **52** is configured by gluing the fluorescent screen **54** and the substrate **56** with the adhesive **58**, the thickness of the fluorescent screen **54** is thick, and the anti-reflection films **26**, **28** are not provided.

Generally, the refractive index of the adhesive **58** is different from the refractive index of the fluorescent screen **54** and the refractive index of the substrate **56**. When the refractive index of the adhesive **58** is different from the refractive index of the fluorescent screen **54**, fluorescence is reflected due to the change in the refractive index at the interface between the fluorescent screen **54** and the adhesive **58**. Similarly, when the refractive index of the adhesive **58** is different from the refractive index of the substrate **56**, fluorescence is reflected due to the change in the refractive index at the interface between the adhesive **58** and the substrate **56**.

The reflected light is further reflected on the front surface of the fluorescent screen **54**, and enters the objective lens **16**. Because the reflected light that has entered the objective lens **16** is not focused on the CCD sensor **14**, components that are not focused on the CCD sensor **14** are mixed in an image formed on the CCD sensor **14**, and the resolution of the image formed on the CCD sensor **14** deteriorates. The reflected light repeats reflection at constant reflectance at each of the interface between the fluorescent screen **54** and the air, the interface between the fluorescent screen **54** and the adhesive **58**, the interface between the adhesive **58** and the substrate **56**, and the interface between the substrate **56** and the air, and spreads in directions that are vertical to the optical axis. Components that are transmitted through the interface between the substrate **56** and the air in this process enter the objective lens **16**. Because fluorescent components that repeated the reflection and have entered the objective lens **16** are not focused on the CCD sensor **14**, components that are not focused on the CCD sensor **14** are mixed in an image formed on the CCD sensor **14**, and the resolution of the image formed on the CCD sensor **14** deteriorates.

On the other hand, because in the radiation detecting element **20** according to the present embodiment, the substrate **22** and the fluorescent screen **24** are bonded by solid state diffusion, the refractive index does not change at the interface between the substrate **22** and the fluorescent screen **24**. Thereby, mixing of components that are not focused on the CCD sensor **14** can be prevented, and the resolution of an image formed on the CCD sensor **14** by the objective lens **16** can be prevented from deteriorating.

FIG. **8** is a schematic diagram for explaining a light-emission position of fluorescence in the radiation detecting apparatus **50** in FIG. **7**. When radiation enters the fluorescent screen **54**, fluorescence is emitted from a plurality of positions that are displaced in the thickness direction of the fluorescent screen **54**. Images of the fluorescence emitted from the plurality of positions displaced in the thickness direction are formed by the objective lens **16** at different positions. Accordingly, by adjusting the position of the objective lens **16** so that an image of fluorescence emitted from a certain position from among the fluorescence emitted from the plurality of positions is formed on the CCD sensor **14**, fluorescence emitted from other positions become components that are not focused on the CCD sensor **14**, and the resolution of an image formed on the CCD sensor **14** deteriorates.

In the radiation detecting apparatus **50** shown in FIG. **8**, the position of the objective lens **16** is adjusted so that fluorescence emitted from a position close to a side surface where radiation enters is imaged on the CCD sensor **14**. In this case, fluorescence emitted from a position that is far from the side surface where radiation enters is formed at a position that is farther from the objective lens **16** than the position of the CCD sensor **14**. Thereby, the resolution of the radiation detecting apparatus **50** deteriorates.

In the radiation detecting element **20** according to the present embodiment, scattering of light-emission points of fluorescence in the traveling direction of radiation can be prevented by reducing the thickness of the fluorescent screen **24**. For example, by making the thickness of the fluorescent screen **24** 1 μm, the spatial resolution of the radiation detecting element **20** can be made equal to the spatial resolution determined by the diffraction limit of fluorescence emitted by the fluorescent screen **24**.

The spatial resolution and sensitivity of the radiation detecting apparatus **10** are in a trade-off relationship with the thickness of the fluorescent screen **24**. When the thickness of the fluorescent screen **24** is small, the spatial resolution increases whereas the amount of emitted light of fluorescence is reduced. For example, if the thickness of the fluorescent screen **24** is 300 μm, 99.4% of a signal of an X-ray with photon energy of 10 KeV can be detected by the fluorescent screen. If the thickness of the fluorescent screen **24** is 20 μm, 29% of a signal of an X-ray with photon energy of 10 KeV can be detected by the fluorescent screen. If the thickness of the fluorescent screen **24** is 1 μm, 1.7% of a signal of an X-ray with photon energy of 10 KeV can be detected by the fluorescent screen. The problem of the detection ratio of an X-ray signal becoming low can be remedied by changing the material used for the fluorescent screen **24** to a material having a greater atomic number or a denser material.

Also, in the present embodiment, the surface of the fluorescent screen **24** where radiation enters is flattened highly accurately in the process of thinning the fluorescent screen **24** by CMP. Thereby, scattering of an entering radiation on the front surface of the fluorescent screen **24** can be suppressed, and the sensitivity and spatial resolution of the radiation detecting apparatus **10** can be increased.

Also, in the present embodiment, the thickness of the substrate **22** is 3 mm, which thickness attenuates radiation that has been transmitted through the fluorescent screen **24** and does not allow passage of the radiation. In a conventional apparatus, fluorescence is reflected on a mirror and allowed to enter the CCD sensor **14** for the purpose of preventing exposure of the objective lens **16** and the CCD sensor **14** to radiation. However, because in the present embodiment, radiation is extinguished at the substrate **22** having high radiation resistance, it does not reach the objective lens **16** or the CCD sensor **14**. For this reason, the radiation detecting apparatus **10** according to the present embodiment can form an image of fluorescence on the CCD sensor **14** by using the objective lens **16** without providing a mirror. Thereby, the radiation detecting apparatus **10** can be downsized, the design freedom of the optical system of the radiation detecting apparatus **10** can be improved, and furthermore, cost reduction can be realized.

Furthermore, the objective lens **16** can be arranged close to the radiation detecting element **20** by not providing a mirror. Thereby, the working distance which is a distance between the objective lens **16** and the radiation detecting element **20** can be decreased, and the numerical aperture of the objective lens **16** can be increased. Thereby, the sensitivity and resolution of the radiation detecting apparatus **10** can be increased.

It should be noted that even in a radiation detecting apparatus in which a mirror is installed between the objective lens **16** and the CCD sensor **14** and the incident direction of fluorescence on the CCD sensor **14** is set to be vertical to the radiation incident direction, the radiation detecting element **20** according to the present embodiment can be used. Thereby, the width of the radiation detecting apparatus can be reduced. Furthermore, even when the working distance is increased in order to attain low magnification and wide viewing field of the radiation detecting apparatus, this can be realized, without increasing the width of the radiation detecting apparatus, by installing a mirror between the objective lens **16** and the CCD sensor **14** and making the incident direction of fluorescence toward the CCD sensor **14** vertical to the radiation incident direction.

Also, in the present embodiment, the thickness of the substrate **22** is decreased as much as possible while ensuring that radiation transmitted through the fluorescent screen **24** is not transmitted through the substrate **22**. When the substrate **22** is made thin, because the optical path within the substrate **22** through which fluorescence emitted from the fluorescent screen **24** is transmitted becomes short, the spherical aberration due to the substrate **22** can be reduced. Because the spherical aberration causes blurring and distortion in an image formed, the resolution of the radiation detecting apparatus **10** can be increased by reducing the spherical aberration. Furthermore, for example, the spherical aberration can be corrected by providing a correction collar to the objective lens **16**. It should be noted that the spherical aberration can be completely corrected by a commercially available objective lens with a correction collar by making the substrate **22** about 500 μm or smaller. Also, the substrate **22** can be thinned up to 300 μm only by means of normal mechanical processing/polishing.

Furthermore, the objective lens **16** can be brought close to the radiation detecting element **20** by making the substrate **22** thin. By further decreasing the working distance, the numerical aperture of the objective lens **16** can be further increased. Thereby, the sensitivity and resolution of the radiation detecting apparatus **10** can be further increased.

Also, because the anti-reflection film **26** is provided in the present embodiment, fluorescence emitted from the fluorescent screen **24** can be prevented from being reflected at the interface between the substrate and the air.

Furthermore, fluorescence emitted from the fluorescent screen **24** in a direction in which radiation enters can be prevented from being reflected at the interface between the fluorescent screen **24** and the air by providing the anti-reflection film **28**. The reflected light becomes components that are not focused on the CCD sensor **14**, and the resolution deteriorates thereby. For this reason, by providing at least one of the anti-reflection film **26** and the anti-reflection film **28**, occurrence of the reflected light can be suppressed, and deterioration of the resolution of the radiation detecting apparatus **10** can be suppressed.

FIG. **9** shows an example of an image captured with the radiation detecting apparatus **10**. The image shown in FIG. **9** is an X-ray photograph of an ant captured by using the radiation detecting apparatus **10** that comprises the radiation detecting element **20** in which the fluorescent screen **24** of 10-μm thickness and the substrate of 2.990-mm thickness are bonded by solid state diffusion. The radiation detecting apparatus **10** has the spatial resolution of 8 μm. The X-ray photograph of the ant is captured by using a one-time 2-mm square beam of SPring-8. Background image difference processing and standardization processing of X-ray intensity in the unit of pixel have been performed on the image that was captured and generated. It can be seen in the X-ray photograph of the ant shown in FIG. **9** that the radiation detecting apparatus **10** can capture an image of the appearance of the feelers, skeleton structure inside feet, and internal organs of the abdominal region of the ant at a high contrast.

While the embodiments of the present invention have been described, the technical scope of the invention is not limited to the above described embodiments. It is apparent to persons skilled in the art that various alterations and improvements can be added to the above-described embodiments. It is also apparent from the scope of the claims that the embodiments added with such alterations or improvements can be included in the technical scope of the invention.

The operations, procedures, steps, and stages of each process performed by an apparatus, system, program, and method shown in the claims, embodiments, or diagrams can be performed in any order as long as the order is not indicated by "prior to," "before," or the like and as long as the output from a previous process is not used in a later process. Even if the process flow is described using phrases such as "first" or "next" in the claims, embodiments, or diagrams, it does not necessarily mean that the process must be performed in this order.

What is claimed is:

1. A manufacturing method of a radiation detecting element comprising:

bonding, by solid state diffusion, a substrate transparent to visible light and a fluorescent screen that emits fluorescence in response to radiation by a dopant added to a material that is the same as a material of the substrate; and

thinning the fluorescent screen, wherein

the bonding includes applying pressure to the substrate and the fluorescent screen.

2. The manufacturing method according to claim **1**, wherein, the bonding includes applying pressure to the substrate and the fluorescent screen in the bonding directions of the substrate and the fluorescent screen.

3. The manufacturing method according to claim **1**, wherein the thinning includes polishing the fluorescent screen.

4. The manufacturing method according to claim **1**, wherein the bonding is performed after a bonding surface of the substrate is superposed on a bonding surface of the fluorescent screen.

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