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(54) **THERMAL RADIATION LIGHT SOURCE**

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(57) **ABSTRACT**

The present invention provides a thermal radiation light source that allows a wider range of material choices than those of conventional techniques, so that light having a desired peak wavelength can easily be obtained. A thermal radiation light source **10** includes a thermo-optical converter made of an optical structure in which a refractive index distribution is formed in a member **11** made of an intrinsic semiconductor so as to resonate with light of a shorter wavelength than a wavelength corresponding to a bandgap of the intrinsic semiconductor. When heat is externally supplied to the thermo-optical converter, light having a spectrum in a band of shorter wavelengths than a cutoff wavelength is produced by interband absorption in the intrinsic semiconductor, and light of a resonant wavelength λ_r in the wavelength band, the light causing resonance in the optical structure, is selectively intensified and emitted as thermal radiation light. In the present invention, an intrinsic semiconductor that provides a wide range of material choices is used, so that a thermal radiation light source that produces narrow-band light having a desired peak wavelength can easily be obtained.

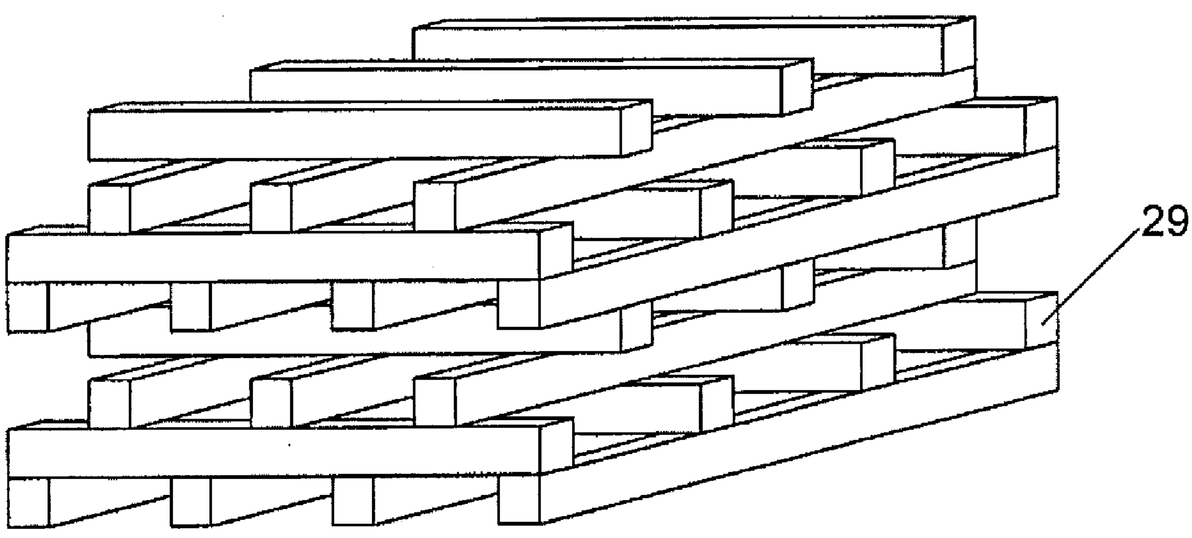


Fig. 1A

CONCEPTUAL DIAGRAM OF WAVELENGTH SPECTRUM OF INTERBAND ABSORPTION IN INTRINSIC SEMICONDUCTOR

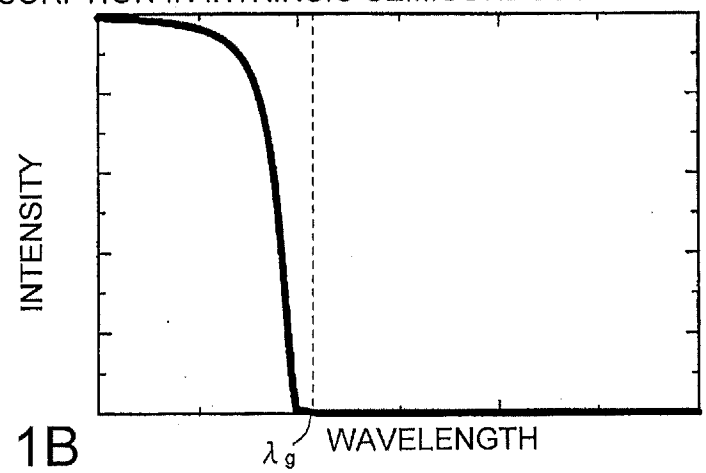


Fig. 1B

CONCEPTUAL DIAGRAM OF WAVELENGTH SELECTION ACCORDING TO PHOTONIC CRYSTAL STRUCTURE

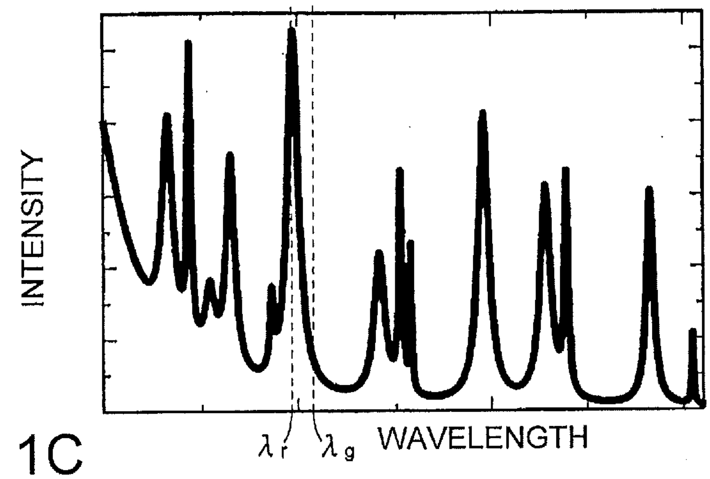


Fig. 1C

CONCEPTUAL DIAGRAM OF WAVELENGTH SPECTRUM OF LIGHT EMISSION FROM THERMAL EMISSION SOURCE ACCORDING TO PRESENT INVENTION

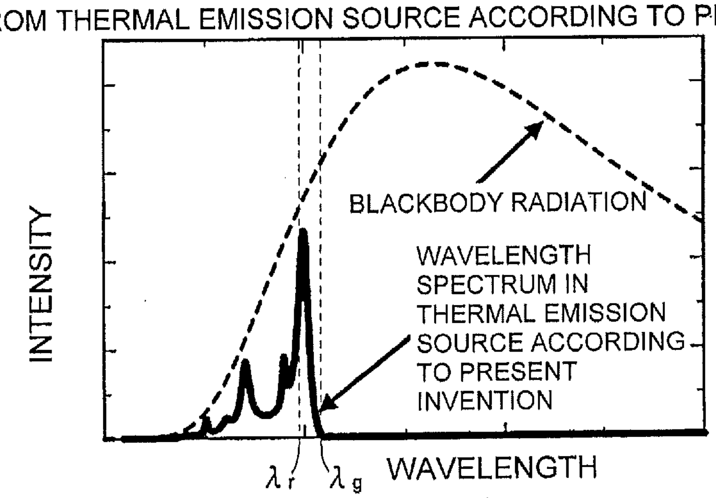


Fig. 2

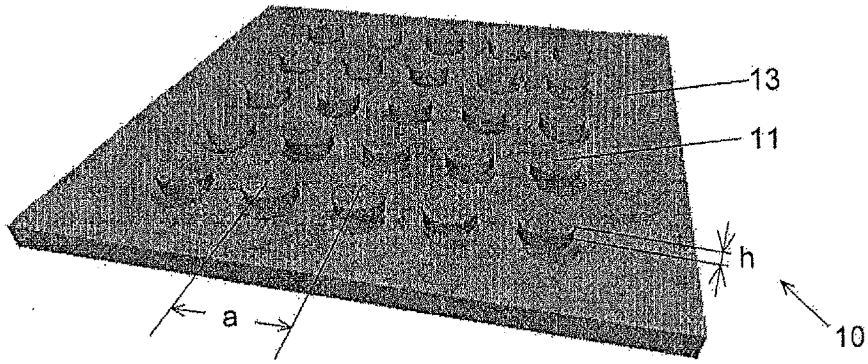


Fig. 3

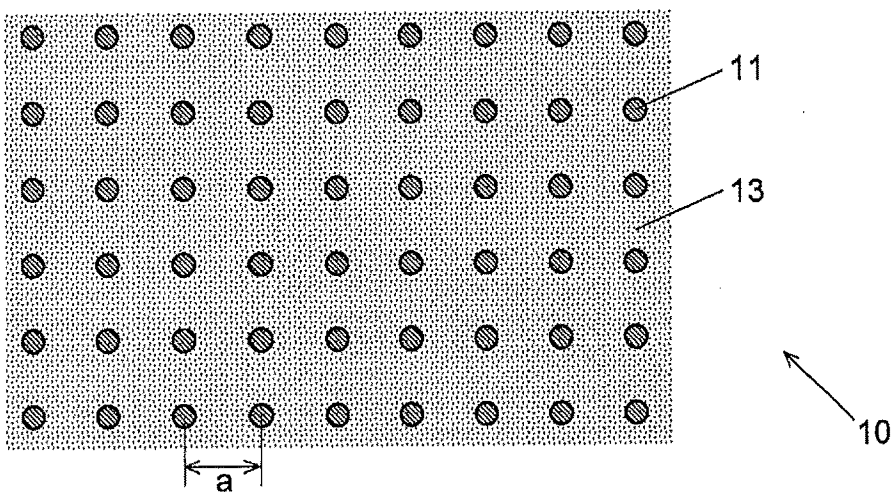


Fig. 4

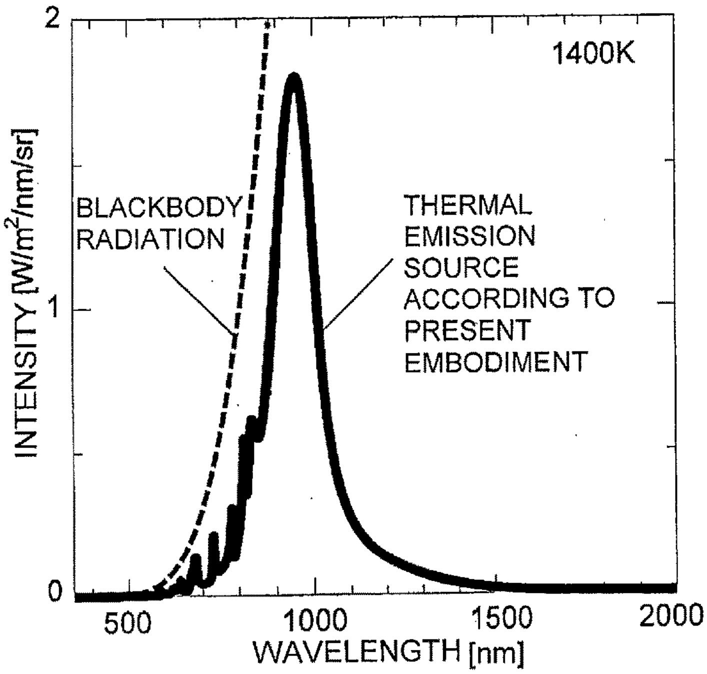


Fig. 5

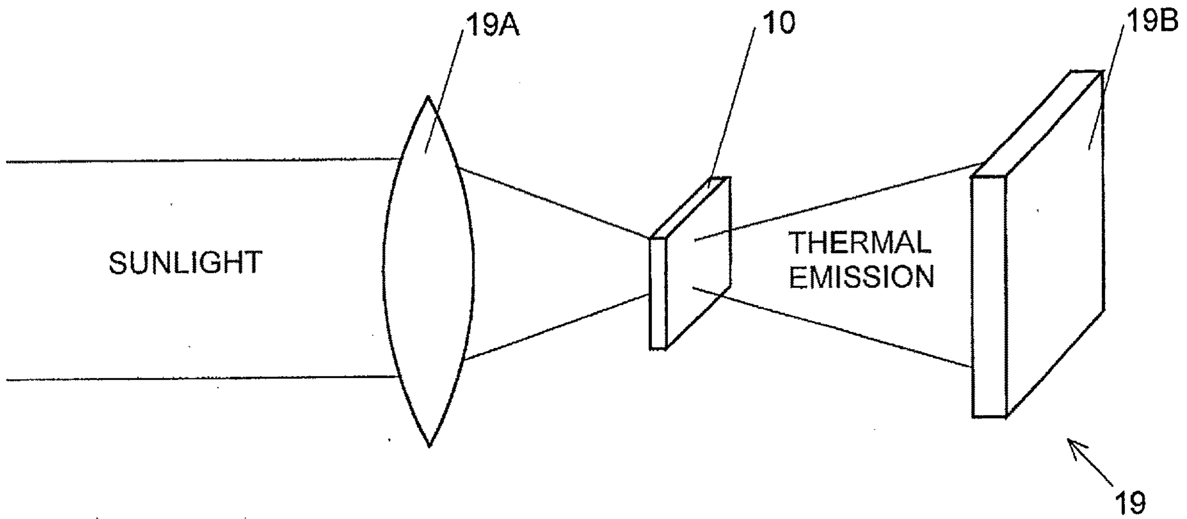


Fig. 6A

(* ADDED)

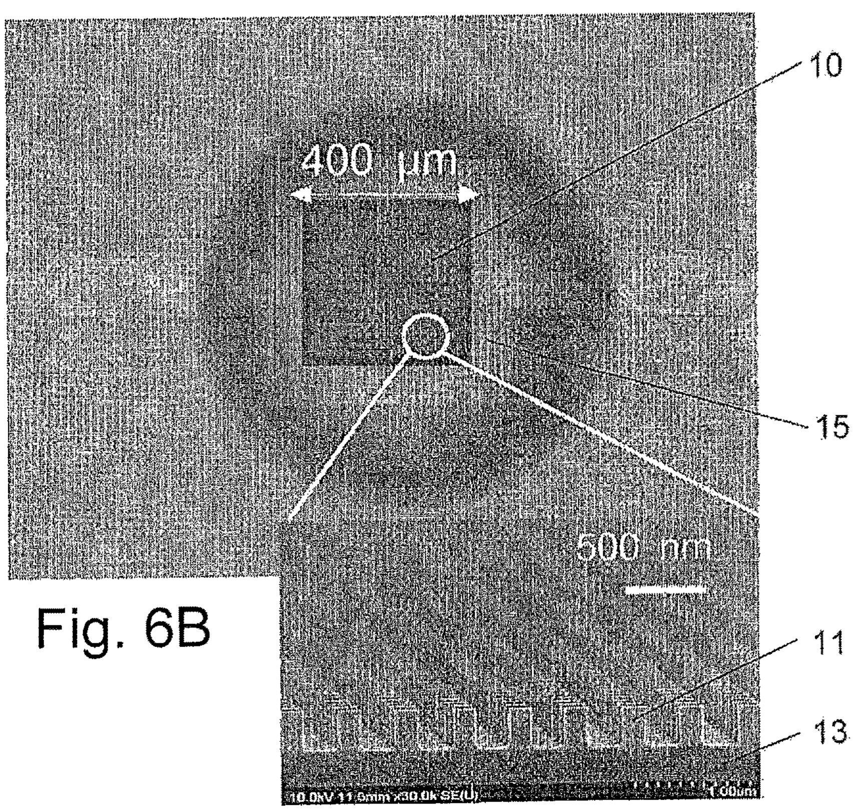


Fig. 6B

Fig. 7

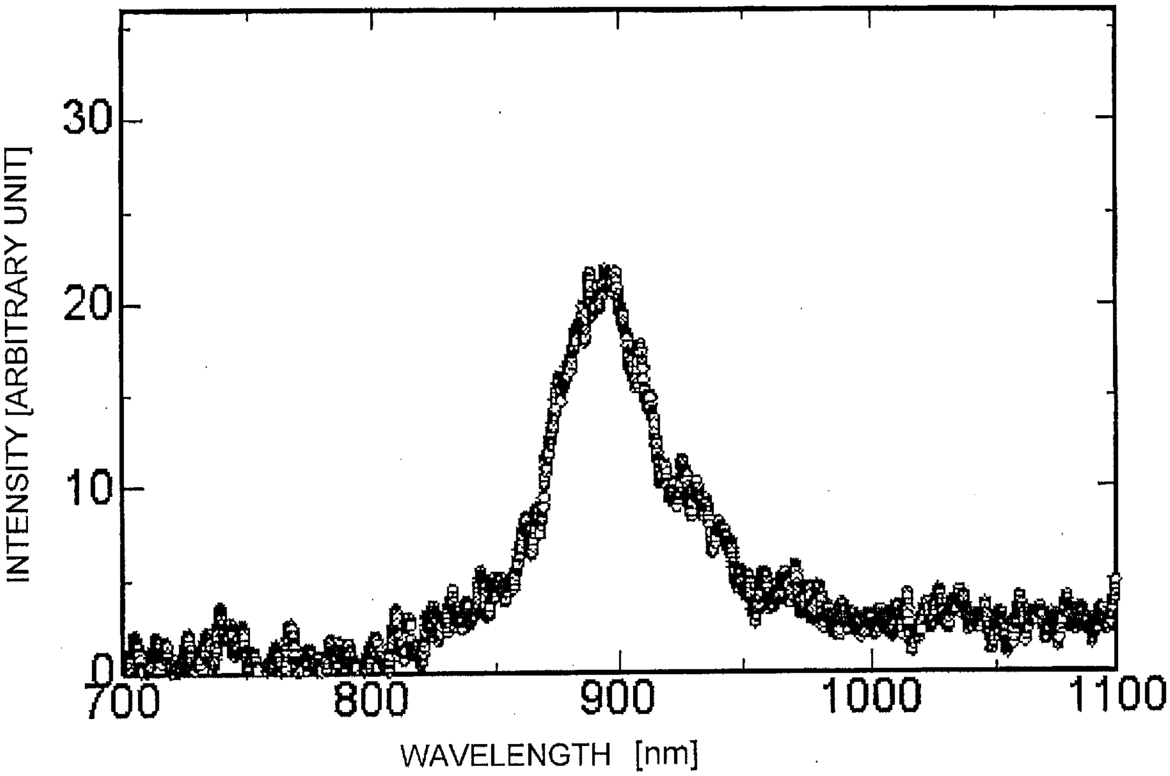

INTENSITY [ARBITRARY UNIT]
30
20
10
0
700
800
900
1000
1100
WAVELENGTH [nm]

Fig. 8

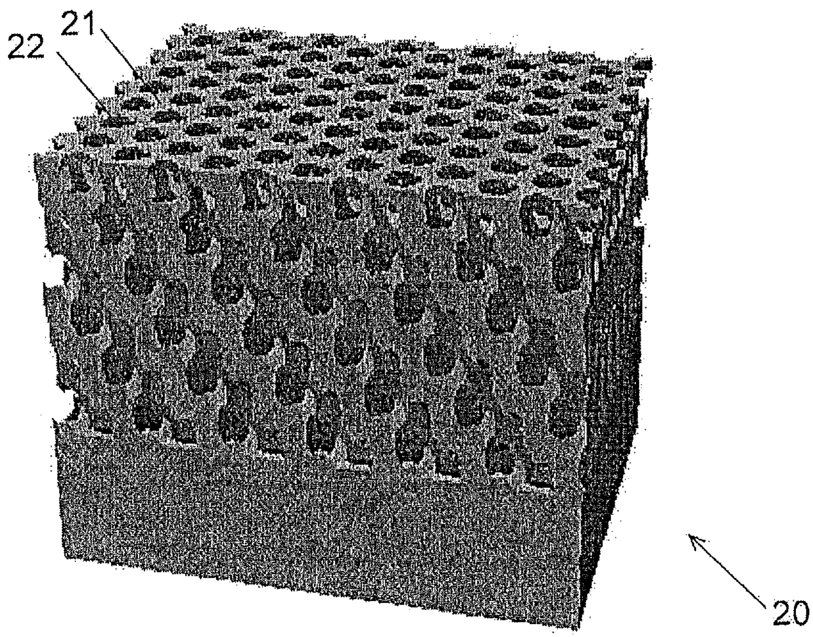

21
22
20

Fig. 9A TOP VIEW

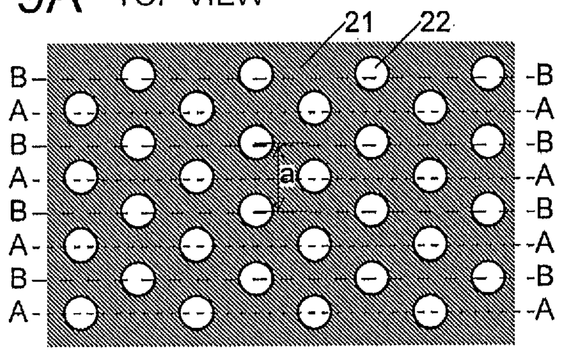


Fig. 9B CROSS-SECTIONAL VIEW ALONG A-A

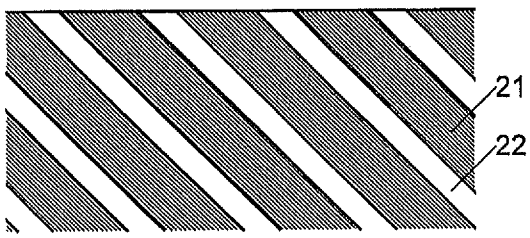


Fig. 9C CROSS-SECTIONAL VIEW ALONG B-B

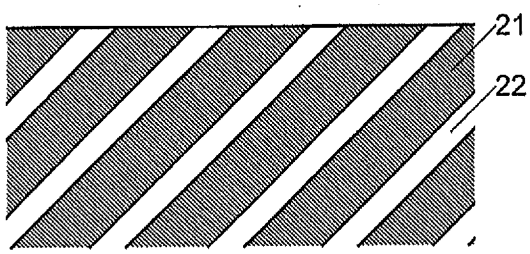


Fig. 10

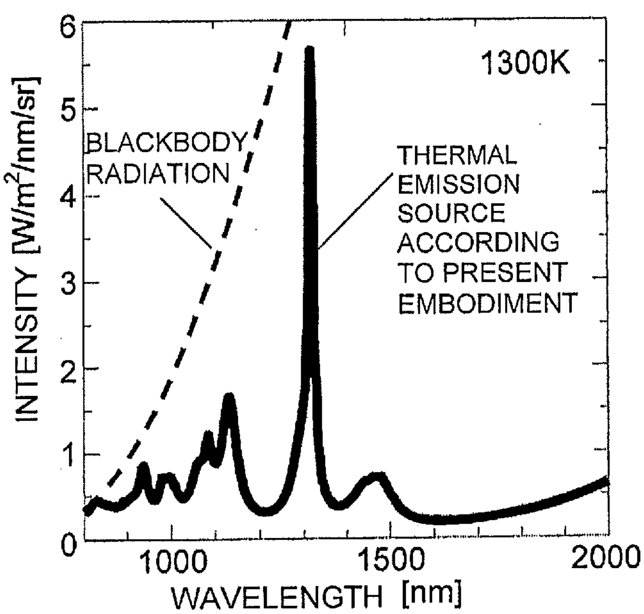


Fig. 11

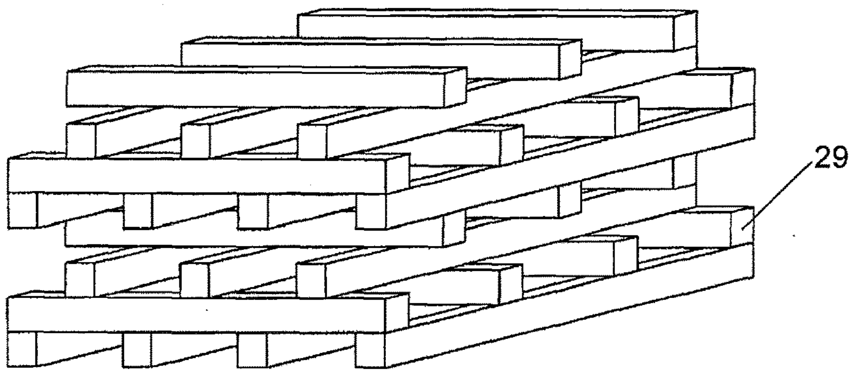


Fig. 12

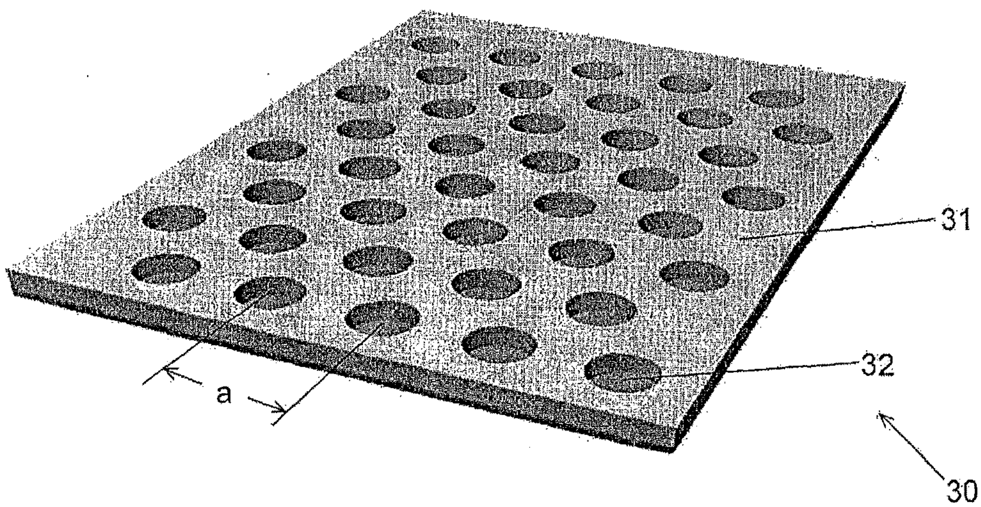
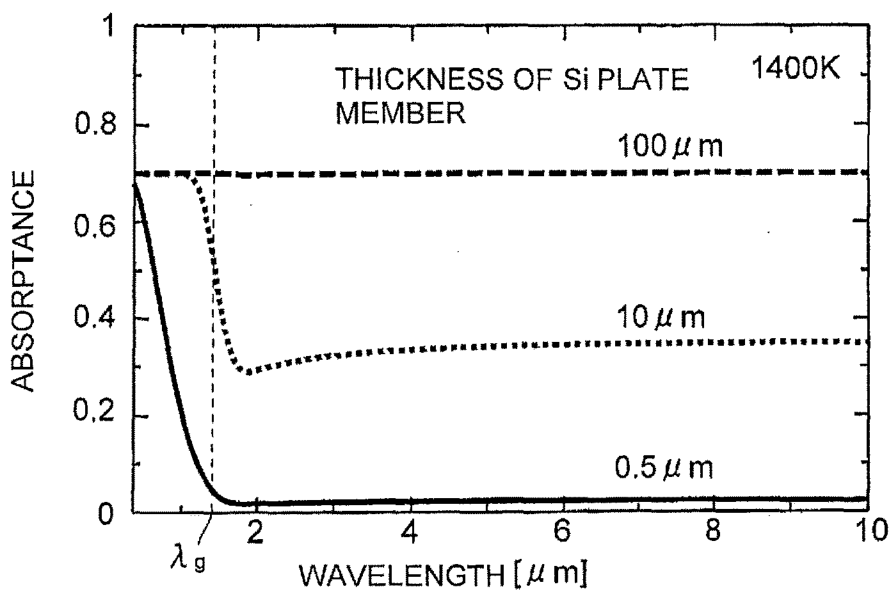


Fig. 13



THERMAL RADIATION LIGHT SOURCE

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application is a divisional application of U.S. application Ser. No. 14/773,663, filed Sep. 8, 2015, the contents of which are incorporated herein by reference.

TECHNICAL FIELD

[0002] The present invention relates to a thermal radiation light source that converts heat to light.

BACKGROUND ART

[0003] In general, heating an object causes thermal radiation which is a radiation of light (electromagnetic waves) having a spectrum that depends on substances constituting the object and the temperature of the object. Thermal radiation generated from an ideal object that completely absorbs light given externally is called a blackbody radiation, and the object is called a blackbody. Blackbody radiation has an intensity distribution over a wide wavelength range, and light having a wavelength spectrum whose distribution is determined only by the temperature is generated. When an ordinary object is heated, it also generates light having a wavelength spectrum distribution over a wide wavelength range; however, it is known that the wavelength spectrum of ordinary object cannot exceed that of a blackbody at a same temperature. Using such thermal radiation, light with a spectrum having an intensity distribution over a wide wavelength range is emitted. That is, a light source (thermal radiation light source) that provides a wide wavelength spectrum can be obtained by a combination of an object and a heat source.

[0004] Meanwhile, instead of light having such wide wavelength spectrum, there has also been a demand for a thermal radiation light source that emits light having a large intensity in a particular wavelength band. Demand of such light source can be found, for example, in the field of solar cells. In solar cells that are currently in practical use, only light in a particular wavelength band in a wide wavelength range of sunlight contributes to photoelectric conversion, and energy of light of other wavelengths is wasted.

[0005] Non-Patent Literatures 1 and 2 each describe a thermal radiation light source including a two-dimensional photonic crystal made of a plate member having a quantum well structure, which is formed by alternately stacking layers of AlGaAs and layers of GaAs, including a plurality of holes formed on a triangular grid in the plate member. When the plate member is heated, thermal excitation of electrons between energy levels in the quantum well causes emission of light having a plurality of wavelengths corresponding to respective differences between the energy levels, where the wavelength spectrum of the emission of light is narrower than those of common thermal radiation light sources. The two-dimensional photonic crystal can resonate with light having a predetermined wavelength determined by a periodicity of holes, and selectively intensify the light of that wavelength. The combination of the quantum well and the two-dimensional photonic crystal provides a wavelength spectrum having a narrow bandwidth around the predetermined wavelength and having a large peak intensity.

CITATION LIST

Patent Literature

[0006] [Patent Literature 1] WO2005/086302
[0007] [Patent Literature 2] WO2007/029661
[0008] [Patent Literature 3] JP 2001-074955

Non Patent Literature

[0009] [Non Patent Literature 1] De Zoysa Menaka et al., "Conversion of broadband to narrowband thermal emission through energy recycling", [online], Jul. 8, 2012, Nature Photonics, [Searched on Feb. 26, 2013], Internet <URL:http://www.nature.com/nphoton/journal/v6/n8/full/nphoton.2012.146.html>

[0010] [Non Patent Literature 2] National University Corporation, University of Kyoto, "Success in significantly narrowing thermal emission spectrum from object—This achieves crucial step toward effective use of energy such as highly-efficient solar cell applications—", [online], Jul. 9, 2012, University of Kyoto New Index 2012, [Searched on Feb. 26, 2013], Internet <URL:http://www.kyoto-u.ac.jp/ja/news_data/h/h1/news6/2012/120709_1.html>

SUMMARY OF INVENTION

Technical Problem

[0011] In the thermal radiation light sources described in Non-Patent Literatures 1 and 2, the peak wavelength of the wavelength spectrum is approximately 10 μm, while the wavelength band contributing to photoelectric conversion in a solar cell is around 1.0 μm if the solar cell is of a generally-used silicon type, and is around 1.5 μm if the solar cell is of a silicon-germanium type. Also, a quantum well structure requires use of two kinds of materials that have respective bandgaps largely different from each other, and thus, as long as a quantum well structure is used, it is difficult to set a peak wavelength to a desired value because combinations of available materials are limited. Therefore, in the thermal radiation light sources described in Non-Patent Literatures 1 and 2, the ratio of light contributing to photoelectric conversion in a solar cell cannot be increased, resulting in failure to achieve photovoltaic power generation with high photoelectric conversion efficiency.

[0012] The aforementioned problem of the difficulty in arbitrarily setting the peak wavelength is not specific to thermal radiation light sources that are used in combination with solar cells, but arises in various uses.

[0013] An object of the present invention is to provide a thermal radiation light source that allows a wide range of material choices so that light having a desired peak wavelength can easily be obtained. The present invention also provides a photovoltaic device using the thermal radiation light source and having high photoelectric conversion efficiency.

Solution to Problem

[0014] In order to attain the aforementioned object, a thermal radiation light source according to the present invention includes a thermo-optical converter having an optical structure in which a refractive index distribution is formed in a member made of an intrinsic semiconductor configured to resonate with light of a shorter wavelength than a wavelength corresponding to a bandgap of the intrinsic semiconductor.

[0015] In the thermal radiation light source according to the present invention, when heat is externally supplied to the thermo-optical converter, energy is absorbed by the intrinsic semiconductor, causing thermal excitation of electrons from the valance band to the conduction band across the bandgap. Such absorption is called "interband absorption". Then, as a result of the transition of the excited electrons to the valance band across the bandgap, light is produced. The light has higher energy than that of the bandgap and thus has wavelengths that are shorter than a wavelength λ_g=hc/E_g (h is the Planck's constant and c is the speed of light) corresponding to the energy E_g of the bandgap. Therefore, the wavelength spectrum of the light generated by the intrinsic semiconductor because of the interband absorption is within a band of wavelengths that are shorter than the wavelength λ_g (FIG. **1**A). Hereinafter, the wavelength λ_g is referred as "cutoff wavelength".

[0016] Then, among the light generated by the interband absorption as stated above, light of wavelengths around a wavelength that causes resonance in the optical structure (hereinafter referred to as "resonant wavelength λ_r"; FIG. **1**B) is selectively intensified and emitted to the outside of the thermo-optical converter (FIG. **1**C). An example of the optical structure is a photonic crystal structure. In the photonic crystal structure, a periodic refractive index distribution is formed, and light of a wavelength λ_r corresponding to the period forms standing waves. Such a photonic crystal structure that allows formation of standing waves of the resonant wavelength λ_r can be created by a person skilled in the art according to, for example, the disclosure of Patent literatures 1 and 2. Also, another example of the optical structure includes one in which a plurality of members having a larger refractive index than that of a base is arranged on the base, which will be described later. In this example, in each member, standing waves formed by light of the wavelength λ_r determined by the size of the member are formed.

[0017] According to the aforementioned principle, the thermal radiation light source according to the present invention produces thermal radiation light having a resonant wavelength λ_r as the peak wavelength and having a wavelength spectrum having a narrower width than that of the spectrum of the thermal radiation.

[0018] In the optical structure, not only light of the resonant wavelength λ_r is generated, but also resonance (higher-order resonance) may occur on the wavelength shorter than the resonant wavelength λ_r. However, the maximal value of intensity of thermal radiation is restricted to the intensity of the blackbody radiation spectrum, and the intensity of the blackbody radiation spectrum sharply decreases on the short wavelength side. Thus, light emission due to higher-order resonance can sufficiently be suppressed.

[0019] The width of the bandgap of the intrinsic semiconductor changes depending on the temperature. The resonant wavelength in the thermo-optical converter is determined by the configuration of the optical structure and thus does not directly depend on the temperature. However, the refractive index changes according to the temperature, and along with the change in the refractive index, the light speed changes. Therefore, the resonant wavelength changes depending on the temperature. Thus, the cutoff wavelength λ_g and the resonant wavelength λ_r may be determined based on the width of the bandgap and the refractive index of the intrinsic semiconductor at the heating temperature when the thermal radiation light source according to the present invention is used.

[0020] The present invention uses an intrinsic semiconductor and allows a wider range of material choices compared to a case where a quantum well structure obtained by combination of two types of semiconductors is used. Thus, a thermal radiation light source that produces light of an intended wavelength can easily be obtained. For the intrinsic semiconductor, any of various materials such as Si (silicon), SiC (silicon carbide) and Cu_2O (copper oxide (I)) can be used. The cutoff wavelength λ_g is approximately 1700 nm (1400 K) in the case of Si, approximately 800 nm (2200 K) in the case of 3C-SiC (SiC having a cubic structure called "3C" from among SiCs), and is approximately 900 nm (1200 K) in the case of Cu_2O. The cutoff wavelength λ_g described here is the value at the temperature indicated in each following bracket, and each of these temperatures is an example which may be used in the thermal radiation light source, which is determined in consideration of a melting point of each intrinsic semiconductor (Si: 1687K, 3C-SiC: 3100K or Cu_2O: 1505K).

[0021] If the resonant wavelength λ_r is too close to the cutoff wavelength λ_g, the portion on the long wavelength side of the wavelength spectrum of the thermal radiation light is cut off. Thus it is desirable that the resonant wavelength λ_r be shorter than the cutoff wavelength λ_g to some extent. For example, it is desirable that the resonant wavelength λ_r be 1600 nm (temperature: 1400 K) or shorter if the intrinsic semiconductor is Si, approximately 750 nm (2200 K) or shorter if the intrinsic semiconductor is 3C-SiC and approximately 850 nm (1200 K) or shorter if the intrinsic semiconductor is Cu_2O.

[0022] It is desirable that the optical structure be asymmetric with respect to the direction in which thermal radiation light is emitted from the thermal radiation light source. If the optical structure has no such asymmetry (that is, if the optical structure is symmetric in the direction), thermal radiation light is emitted both in the direction and in the direction opposite to the direction with the same intensity. If the optical structure has such asymmetry, thermal radiation light is emitted in one direction with a larger intensity.

[0023] An example of the optical structure is a two-dimensional photonic crystal structure formed by periodically providing, in a plate member made of an intrinsic semiconductor, areas each having a refractive index that is different from that of the plate member (different refractive index area). For each of the different refractive index areas, a hole (air or vacuum) can be used, or a member made of a material that is different from the intrinsic semiconductor can be used. In this example, standing waves of a wavelength determined by the length of periodicity of the different refractive index areas are formed in the thermo-optical converter. Also, it is desirable that in the photonic crystal structure of this example, the different refractive index areas be asymmetric with respect to the direction perpendicular to the plate member. Consequently, thermal radiation light can be emitted to one surface of the plate member with a larger intensity. Examples of the different refractive index areas having such asymmetry includes those having a triangular or trapezoidal shape in the cross-section perpendicular to the plate member; however, different refractive index areas that open in one surface of the plate member and do not open in the other surface of the plate member are desirable in terms of easy fabrication.

[0024] For the optical structure, it is desirable to use such a structure that, on a surface of a base made of material having a refractive index lower than that of the intrinsic semiconductor, members (high-refractive index members) made of the intrinsic semiconductor and having the same shape are two-dimensionally arranged. The arrangement of the high-refractive index members does not need to be periodic. Such configuration allows formation of standing waves of a wavelength corresponding to the size of the high-refractive index members within each high-refractive index member. Therefore, the high-refractive index member itself can be made to function as an optical resonator (high-refractive index member optical resonator), enabling light whose wavelength of the standing waves is resonant wavelength to be selectively amplified. Since the optical structure is asymmetric as stated above, thermal radiation light can be emitted in one direction with a larger intensity.

[0025] For the optical structure, a three-dimensional photonic crystal structure having a three-dimensional periodic refractive index distribution may be used. In the three-dimensional photonic crystal structure, a wavelength band in which light cannot exist within the structure can be formed irrespective of the direction of polarization of light. Such a wavelength band is formed for light for the reason similar to the bandgap for electrons, and is called "photonic bandgap" to distinguish from the bandgap for electrons. In the present invention, use of a three-dimensional photonic crystal structure enables selectively amplifying light of a predetermined wavelength that causes resonance in the three-dimensional photonic crystal structure (that is, light of a wavelength that can exist in the three-dimensional photonic crystal structure) while preventing production of light of wavelengths in the photonic bandgap, whereby light of the predetermined wavelength can efficiently be produced.

[0026] Combining the thermal radiation light source according to the present invention with a solar cell, a highly-efficient photovoltaic device can be obtained. In other words, the photovoltaic device includes a thermo-optical converter according to the present invention, and a solar cell for performing photoelectric conversion by receiving light produced by the thermo-optical converter and using the light having a wavelength band including the resonant wavelength.

[0027] In the photovoltaic device according to the present invention, the solar cell receives light with the wavelength spectrum having a narrower width (but capable of making photoelectric conversion) than that of the wavelength spectrum of sunlight and including the resonant wavelength from the thermo-optical converter, the intensity of light having the wavelength band that makes photoelectric conversion is enhanced compared to a case where the solar cell directly receives sunlight. Thus, the photoelectric conversion efficiency is enhanced compared to a case where the solar cell directly receives sunlight. For example, a silicon solar cell cannot perform photoelectric conversion at wavelengths about 1000 nm or longer, and thus it is desirable to set the resonant wavelength λ_r of the thermo-optical converter at 1000 nm or shorter.

Advantageous Effects of Invention

[0028] The present invention enables use of an intrinsic semiconductor that allows a wider range of material choices, enabling easy provision of a thermal radiation light source that produces narrow-band light having a desired peak wavelength.

[0029] The present invention also enables provision of a photovoltaic device having a higher photoelectric conversion efficiency than that in a case where a solar cell directly receives sunlight.

BRIEF DESCRIPTION OF DRAWINGS

[0030] FIG. **1**A, FIG. **1**B and FIG. **1**C are diagrams for describing a reason that light having a particular wavelength band is produced in a thermal radiation light source according to the present invention, and FIG. **1**A is a conceptual diagram of a wavelength spectrum of interband absorption in an intrinsic semiconductor, FIG. **1**B is a conceptual diagram of wavelength selection according to an optical structure, and FIG. **1**C is a conceptual diagram of a wavelength spectrum of light emission by the thermal radiation light source according to the present invention.

[0031] FIG. **2** is a perspective diagram illustrating a thermal radiation light source according to a first embodiment.

[0032] FIG. **3** is a plan view of the thermal radiation light source according to the first embodiment.

[0033] FIG. **4** is a graph showing an example of a wavelength spectrum obtained, by calculation, by the thermal radiation light source according to the first embodiment.

[0034] FIG. **5** is a schematic configuration diagram illustrating an example of a photovoltaic device using the thermal radiation light source according to the first embodiment. FIG. **6**A and FIG. **6**B are an optical photomicrograph and an electron photomicrograph respectively taken of the thermal radiation light source produced in the first embodiment.

[0035] FIG. **7** is a graph showing a result of measurement of a wavelength spectrum obtained by the thermal radiation light source produced in the first embodiment.

[0036] FIG. **8** is a perspective view of a thermal radiation light source according to a second embodiment.

[0037] FIG. **9**A is a top view of the thermal radiation light source of the second embodiment, FIG. **9**B is a cross-sectional view along plane A-A, and FIG. **9**C is a cross-sectional view along plane B-B.

[0038] FIG. **10** is a graph showing an example of a wavelength spectrum obtained, by calculation, by the thermal radiation light source according to the second embodiment.

[0039] FIG. **11** is a perspective diagram illustrating an alteration of the thermal radiation light source according to the second embodiment.

[0040] FIG. **12** is a perspective diagram illustrating a thermal radiation light source according to a third embodiment.

[0041] FIG. **13** is a graph showing differences in absorptance among plate members having different thicknesses.

DESCRIPTION OF EMBODIMENTS

[0042] Embodiments of a thermal radiation light source according to the present invention will be described with reference to FIG. **2** to FIG. **13**.

Embodiment 1

[0043] As illustrated in FIG. **2** and FIG. **3**, a thermal radiation light source **10** according to a first embodiment has an optical structure in which a plurality of columnar rods **11** made of an intrinsic semiconductor is arranged on a surface of a base **13** having a lower refractive index than that of the intrinsic semiconductor. In the present embodiment, for a material of the rod **11**, Si (refractive index: 3.4) is used, and for a material of the base **13**, SiO_2 (refractive index: 1.5) is used. A radius r of the rods **11** is 100 nm and a height h of the rods is 500 nm. In the present embodiment, the rods **11** are arranged at grid points of a square grid whose period length "a" is 600 nm; however, such periodic arrangement of the rods **11** is not essential to the present invention.

[0044] From among the above parameters, a resonant wavelength λ_r in the optical structure in the present embodiment is determined by the refractive index n and the radius r of the rods **11** and the period length "a" of the square grid as described below.

[0045] In the thermo-optical converter, light propagates in a height direction of the rods **11** along the rods **11** having a higher refractive index than that of the surrounding areas. Then, the light is reflected by an upper end and a lower end of each rod **11**, whereby standing waves are generated and a resonant state of the light is formed. The resonant wavelength λ_r depends on the height h of the rods **11** and also depends on the radius r of the rods **11** since the effective refractive index varies when the light leaks from the rods **11**. A difference in period length "a" of the rods **11** affects the resonant wavelength λ_r in terms of a difference in effective refractive index, but not so largely as a difference in radius r of the rods **11** does. The rods **11** having an excessively short period length "a" causes the wide range of electromagnetic field overlapped distribution among the rods **11** and interaction thereby occurs, resulting in variation in the resonant wavelength depending on the emission angle of the light. On the other hand, the period length "a" having a longer period length than that of a light emission wavelength invokes high-order diffraction, whereby radiation in one resonant mode is generated in a plurality of directions. Therefore, it is desirable that the period length "a" be longer than a distance of oozing of an electromagnetic field from each rod and be shorter than the light emission wavelength.

[0046] In the present embodiment, the radius r of the rods **11** is set to 100 nm and the height h of the rods is set to 500 nm, whereby the wavelength λ_r of a resonant mode generated in each rod becomes 950 nm. Furthermore, the period length "a" is set to 600 nm, which is shorter than the resonant wavelength λ_r and sufficiently larger than the rod radius, whereby emission angle dependency is suppressed while the light emission intensity is maintained.

[0047] A principle of heat to light conversion by the thermal radiation light source **10** according to the first embodiment will be described. When the thermal radiation light source **10** is heated to a temperature of around 1400 K, energy absorption caused by interband absorption in Si, which is an intrinsic semiconductor on the wavelength shorter than a cutoff wavelength λ_g for Si≈1700 nm (on the high energy side that is higher than 0.73 eV, which is photon energy corresponding to the cutoff wavelength λ_g) occurs, and light emission corresponding to the energy occurs on the wavelength shorter than the cutoff wavelength λ_g (high energy side). A spectrum of the light generated as above, as indicated in FIG. **1**A, continues on the wavelength shorter than λ_g, and in such continuous wavelength band, a wavelength spectrum with around a resonant wavelength $\lambda_r \approx 950$ nm as a maximal value (peak top) can be obtained by the optical structure according to the present embodiment.

[0048] An example of a wavelength spectrum that can be obtained, by calculation, by the thermal radiation light source **10** according to the first embodiment is indicated in FIG. **4**. In this example, the calculation is performed for a case where the thermal radiation light source **10** is heated to 1400 K (1127° C.). As indicated in the figure, the wavelength spectrum has a single peak with a wavelength of approximately 950 nm as a peak top. The cutoff wavelength λ_g of Si is approximately 1700 nm (the corresponding photon energy is approximately 0.73 eV), and almost no light emission occurs on the wavelength longer than the cutoff wavelength λ_g. Also, on the low wavelength side relative to the peak, the spectrum of blackbody radiation becomes smaller as the wavelength is shorter, and the wavelength spectrum of the thermal radiation light source **10** becomes smaller accordingly as the wavelength is shorter.

[0049] As described above, the thermal radiation light source **10** according to the present embodiment can selectively emit only wavelengths that are around the resonant wavelength λ_r=950 nm. A silicon solar cell cannot perform photoelectric conversion of light of wavelengths exceeding approximately 1000 nm. Therefore, as illustrated in FIG. **5**, a photovoltaic device **19** can be constructed by the thermal radiation light source **10**, a collective lens **19**A that collects sunlight to the thermal radiation light source **10**, and a silicon solar cell **19**B that receives thermal radiation light from the thermal radiation light source **10**. Consequently, photoelectric conversion can be performed in the silicon solar cell **19**B after conversion of sunlight having a wide wavelength spectrum including light of wavelengths exceeding approximately 1000 nm to light having a peak of a wavelength spectrum at a wavelength of 1000 nm or shorter (950 nm in the present embodiment) by the thermal radiation light source **10**, enabling enhancement in efficiency of the photoelectric conversion.

[0050] Next, a result of measurement using an actually-produced thermal radiation light source **10** will be described with reference to FIG. **6**A, FIG. **6**B and FIG. **7**. FIG. **6**A is an optical photomicrograph taken of the produced thermal radiation light source **10**, and FIG. **6**B is a magnified electron photomicrograph taken of the rods **11** and the base **13** of the thermal radiation light source **10**. In the produced thermal radiation light source **10**, columnar rods **11** made of Si are arranged in a square grid in a square area 400 μm on a side on a surface of a plate base **13** made of SiO_2 and has a thickness of approximately 3 μm. A radius r of the rods **11** is 100 nm, a height h is 450 nm, and a periodic length "a" of the square grid is 500 nm. Also, a plate heater **15** having a three-layer structure constructed of a layer of Ti, a layer of Pt and a layer of Ti in this order from the side close to the base **13** is provided, so as to be contact with a lower surface of the base **13** (surface on the opposite side of the surface on which the rods are provided). When current was flown to the heater **15**, the thermal radiation light source **10** was heated to a temperature of approximately 500 K, and the heat was converted to light according to the above-described principle, whereby light emission was obtained. When a spectrum of the obtained light emission was measured, as shown in FIG. **7**, a wavelength spectrum having a peak at a wavelength of approximately 900 nm was obtained.

[0051] Although an example in which Si is used for the material of the rods **11** has been described up to here, an intrinsic semiconductor other than Si such as SiC or Cu_2O may be used. If 3C-SiC is used for the material of the rods **11**, the cutoff wavelength λ_g is 800 nm, which is shorter than that in the case of Si, and thus, the height and the radius of the rods **11** is set to be small compared to those in the case of Si. This obtains a thermal radiation light source that produces thermal radiation light having a wavelength spectrum with a peak on the wavelength shorter than 750 nm. A thermal radiation light source having such characteristics as above can suitably be used as a light source that emits thermal radiation light resulting from conversion of sunlight to a GaAs solar cell.

[0052] Also, although in the first embodiment, the rods **11** are arranged in a square grid, arrangement in, e.g., a triangular grid may be employed. Also, although the shape of the rods **11** is a columnar shape, a shape such as a square rod, a cone or a pyramid may be employed. Furthermore, the surrounding areas of the rods **11** may be filled with a material having a lower refractive index than that of the rods **11**, such as SiO_2.

Embodiment 2

[0053] As illustrated in FIG. **8** and FIG. **9**, a thermal radiation light source **20** according to a second embodiment has a structure in which columnar holes **22** each extending in a direction inclined by 45° from the normal to an upper surface of a block-member **21** made of an intrinsic semiconductor are periodically formed. The columnar holes **22** are arranged in a triangular grid with a period length "a" in the upper surface of the block member **21**. Also, directions in which the columnar holes **42** in adjacent rows with grid points in the triangular grid extend are different by 90° from each other (alternation of the cross-sections along A-A and the cross-sections along B-B in FIG. **9**A) (FIG. **9**A and FIG. **9**C). Such configuration allows formation of a three-dimensional photonic crystal structure having a three-dimensional periodic refractive index distribution in a blocked member **21** made of an intrinsic semiconductor (optical structure in the present embodiment). In the present embodiment, a material of the block member **21** is Si, and a period length "a" is 680 nm.

[0054] An example of a wavelength spectrum obtained by the thermal radiation light source **20** according to the second embodiment is indicated in FIG. **10**. In this example, a wavelength spectrum if the thermal radiation light source **20** is heated to 1300 K (1027° C.) was obtained by calculation. As illustrated in the figure, a wavelength spectrum with a wavelength of approximately 1300 nm as a peak top was obtained.

[0055] The material of the block member **21** is not limited to Si mentioned above and, e.g., SiC or Cu_2O may be used. Also, instead of the columnar holes **22**, members having a lower refractive index than that of the block member **21** may be used. Alternatively, as illustrated in FIG. **11**, a three-dimensional photonic crystal in which layers having rod members **29** each made of an intrinsic semiconductor and arranged in parallel are stacked may be used, where a direction of the rod members in a layer is different by 90° from that of the rod members in a longitudinally adjacent layer (see Patent Literature 3).

Embodiment 3

[0056] As illustrated in FIG. **12**, a thermal radiation light source **30** according to a third embodiment has a configuration in which holes (different-refractive index areas) **32** is periodically provided in a plate member **31**, whereby a two-dimensional photonic crystal structure (optical structure in the present embodiment) is formed. For a material of the plate member **31**, in the present embodiment, Si (refractive index: 3.4) is used. The holes **32** are arranged in a triangular grid. A planar shape of the individual holes **32** is a round shape. In this configuration, in the thermal radiation light source **30** according to the present embodiment, holes **32** each having a refractive index of approximately 1 are periodically arranged in the Si plate member **31** made of an intrinsic semiconductor and has the refractive index of 3.4, whereby a two-dimensional periodic refractive index distribution is formed.

[0057] In the present embodiment, a period length "a" of the holes **32** is set to 600 nm. Also, a radius of the holes **32** is set to 150 nm. Also, the plate member **31** has a thickness of 500 nm, and the holes **32** are formed to have a depth of 200 nm from one surface of the plate member **31**. The holes **32** are provided so as to form openings in one surface of the plate-like member **31** and not form the openings in the other surface, which forms asymmetry in a direction perpendicular to the plate member **31**. Thus, thermal radiation light can be emitted with a larger intensity from the surface of the plate member **31** through which the holes **32** extend. In the present embodiment, as a diameter of the holes **32** is larger, an average refractive index in a case of combining the plate member **31** and the holes **32** is smaller, and thus, if the period length "a" remains constant, as the diameter is larger, the wavelengths in air is shorter.

[0058] In the present embodiment, only light of wavelengths close to a resonant wavelength λ_r=1600 nm on the wavelength shorter than a cutoff wavelength $\lambda_g \approx$1700 nm is selected and amplified and emitted to the outside.

[0059] The thickness of the plate-like member **31** can be changed within a certain range while the resonant wavelength is maintained to be similar, by adjusting, e.g., the diameter, depth or periodicity of the holes. However, excessive increase in the thickness causes energy absorption by intrinsic carriers in the intrinsic semiconductor, which may result in undesired light emission on the wavelength longer than the cutoff wavelength λ_g. As an example, each energy absorptance of a Si plate member having a thickness of 0.5 μm (500 nm), which is the same as that of the present embodiment, and Si plate members having a thickness of 10 μm and 100 μm, respectively, when the members are heated to 1400 K (1127° C.) was obtained by calculation. As shown in FIG. **13**, on the longer wavelength side than the cutoff wavelength λ_g for Si≈1700 nm (corresponding photon energy: 0.73 eV), the absorptance has a value of almost 0.7 where the thickness of the plate member is 100 μm, and the absorptance has a value of 0.30 to 0.35 where the thickness is 10 μm, whereas the absorptance has a value of almost zero where the thickness is 0.5 μm. This means that as the thickness of the plate member is larger, undesired light emission on the long wavelength side occurs with larger intensity. Therefore, in order to suppress such light emission, it is desirable that the thickness of the plate member **31** be thin. However, if the thickness of the plate member **31** is extremely small, light emission having the resonant wavelength also decreases, and thus, it is desirable to select a proper thickness in view of this point. In the present embodiment, 0.5 μm is optimum.

[0060] Such unnecessary light emission on the long wavelength side may occur in the first and second embodiments. In the first embodiment, an effective thickness of intrinsic semiconductor averaged in a direction parallel to a surface of the base **13** can be changed by changing the height or diameter of the rods **11** made of the intrinsic semiconductor, enabling adjustment so that light emission on the long wavelength side is suppressed. In the second embodiment, the periodicity of the columnar holes **22** or the rod members **29** is adjusted so that a three-dimensional photonic bandgap is formed on the wavelength longer than the resonant wavelength, whereby light on the longer wavelength cannot exist in the three-dimensional photonic crystal structure. Therefore, production of the light is thus suppressed.

[0061] Although an example in which Si is used for the material of the plate member **31** has been described up to here, an intrinsic semiconductor other than Si such as SiC or Cu_2O may be used. Also, although an example in which the holes **32** are arranged in a triangular grid has been described up to here, arrangement in, e.g., a square gird may be employed. Although a planar shape of the holes **32** is a round shape, a planar shape other than a round shape such as a regular triangle shape may be employed. Furthermore, instead of the holes **32**, members having a lower refractive index than that of the material of the plate member **31** such as members made of SiO_2 may be provided.

REFERENCE SIGNS LIST

[0062] **10**, **20**, **30** . . . Thermal radiation light source
[0063] **11** . . . Rod
[0064] **13** . . . Base
[0065] **15** . . . Heater
[0066] **19** . . . Photovoltaic Device
[0067] **19**A . . . Collective Lens
[0068] **19**B . . . Silicon Solar Cell
[0069] **21** . . . Block Member
[0070] **22** . . . Columnar Hole
[0071] **29** . . . Rod Member
[0072] **31** . . . Plate Member
[0073] **32** . . . Hole

1. A power generation device comprising:
a thermo-optical converter having an optical structure in which a refractive index distribution is formed in a member made of an intrinsic semiconductor configured to resonate with light of a shorter wavelength than a wavelength corresponding to a bandgap of the intrinsic semiconductor; and
a solar cell configured to perform photoelectric conversion by receiving light produced by the thermo-optical converter and using the light having a wavelength band including a resonant wavelength that causes resonance in the optical structure.

2. The power generation device according to claim **1**, wherein the optical structure has asymmetry in a direction in which thermal radiation light is emitted from the thermo-optical converter.

3. The power generation device according to claim **1**, wherein the optical structure has such a structure that, on a surface of a base made of material having a refractive index lower than that of the intrinsic semiconductor, members made of the intrinsic semiconductor are two-dimensionally arranged.

4. The power generation device according to claim **1**, wherein the optical structure is a two-dimensional photonic crystal structure formed by periodically providing, in a plate member made of an intrinsic semiconductor, different refractive index areas having refractive index different from the plate member, wherein the different refractive index areas have an asymmetric shape in a direction perpendicular to the plate member.

5. The power generation device according to claim **4**, wherein the different refractive index areas are formed so as to open in a surface of the plate member and not to open in the other surface of the plate member.

6. The power generation device according to claim **1**, wherein the optical structure is a three-dimensional photonic crystal structure having a three-dimensional periodic refractive index distribution.

7. The power generation device according to claim **1**, wherein the intrinsic semiconductor is Si, and the resonant wavelength is 1000 nm or shorter.

8. The power generation device according to claim **1**, wherein the intrinsic semiconductor is 3C-SiC, and the resonant wavelength is 750 nm or shorter.

9. The power generation device according to claim **3**, wherein the base includes a plate heater having a three-layer structure including a layer including Ti, a layer including Pt and a layer including Ti in this order from a side close to the base.

10. A power generation method comprising:
emitting, to an outside of a thermo-optical converter having an optical structure in which a refractive index distribution is formed in a member made of an intrinsic semiconductor configured to resonate with light of a shorter wavelength than a wavelength corresponding to a bandgap of the intrinsic semiconductor, a light with a resonant wavelength that causes resonance in the optical structure by supplying heat;
receiving the light emitted from the thermo-optical converter by a solar cell; and
performing, by the solar cell, photoelectric conversion using a light having a wavelength band including the resonant wavelength.

11. The power generation method according to claim **10**, wherein the optical structure has asymmetry in a direction in which thermal radiation light is emitted from the thermo-optical converter.

12. The power generation method according to claim **10**, wherein the optical structure has such a structure that, on a surface of a base made of material having a refractive index lower than that of the intrinsic semiconductor, members made of the intrinsic semiconductor are two-dimensionally arranged.

13. The power generation method according to claim **10**, wherein the optical structure is a two-dimensional photonic crystal structure formed by periodically providing, in a plate member made of an intrinsic semiconductor, different refractive index areas having refractive index different from the plate member, wherein the different refractive index areas have an asymmetric shape in a direction perpendicular to the plate member.

14. The power generation method according to claim **13**, wherein the different refractive index areas are formed so as to open in a surface of the plate member and not to open in the other surface of the plate member.

15. The power generation method according to claim **10**, wherein the optical structure is a three-dimensional photonic crystal structure having a three-dimensional periodic refractive index distribution.

16. The power generation method according to claim **10**, wherein the intrinsic semiconductor is Si, and the resonant wavelength is 1000 nm or shorter.

17. The power generation method according to claim **10**, wherein the intrinsic semiconductor is 3C-SiC, and the resonant wavelength is 750 nm or shorter.

18. The power generation method according to claim **12**, wherein the base includes a plate heater having a three-layer structure including a layer including Ti, a layer including Pt and a layer including Ti in this order from a side close to the base.

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