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Sugahara et al.

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(54) **THERMOELECTRIC CONVERSION DEVICE**

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CPC ***H10N 10/17*** (2023.02); ***H10N 10/82*** (2023.02)

(58) **Field of Classification Search**
CPC H10N 10/10; H10N 10/17; H10N 10/82
See application file for complete search history.

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Primary Examiner — Mayla Gonzalez Ramos
(74) *Attorney, Agent, or Firm* — WHDA, LLP

(57) **ABSTRACT**

A thermoelectric conversion device includes thermoelectric layers and connection layers that are alternately provided in a first direction parallel to surfaces of the thermoelectric layers, and are connected to each other, thermally conductive layers that are connected to the respective connection layers, and extends in a second direction intersecting the surfaces, a first insulating layer that has a smaller thermal conductivity than the thermally conductive layers, and a second insulating layer that has a smaller thermal conductivity than the first insulating layer, is provided between the first insulating layer and the thermoelectric layers, and has a thickness equal to or greater than ¼ of a distance between an end of the thermally conductive layer at a side of one of the thermoelectric layers and a center of another of the connection layers in the first direction, the thermally conductive layers penetrating through the first and second insulating layers.

15 Claims, 10 Drawing Sheets

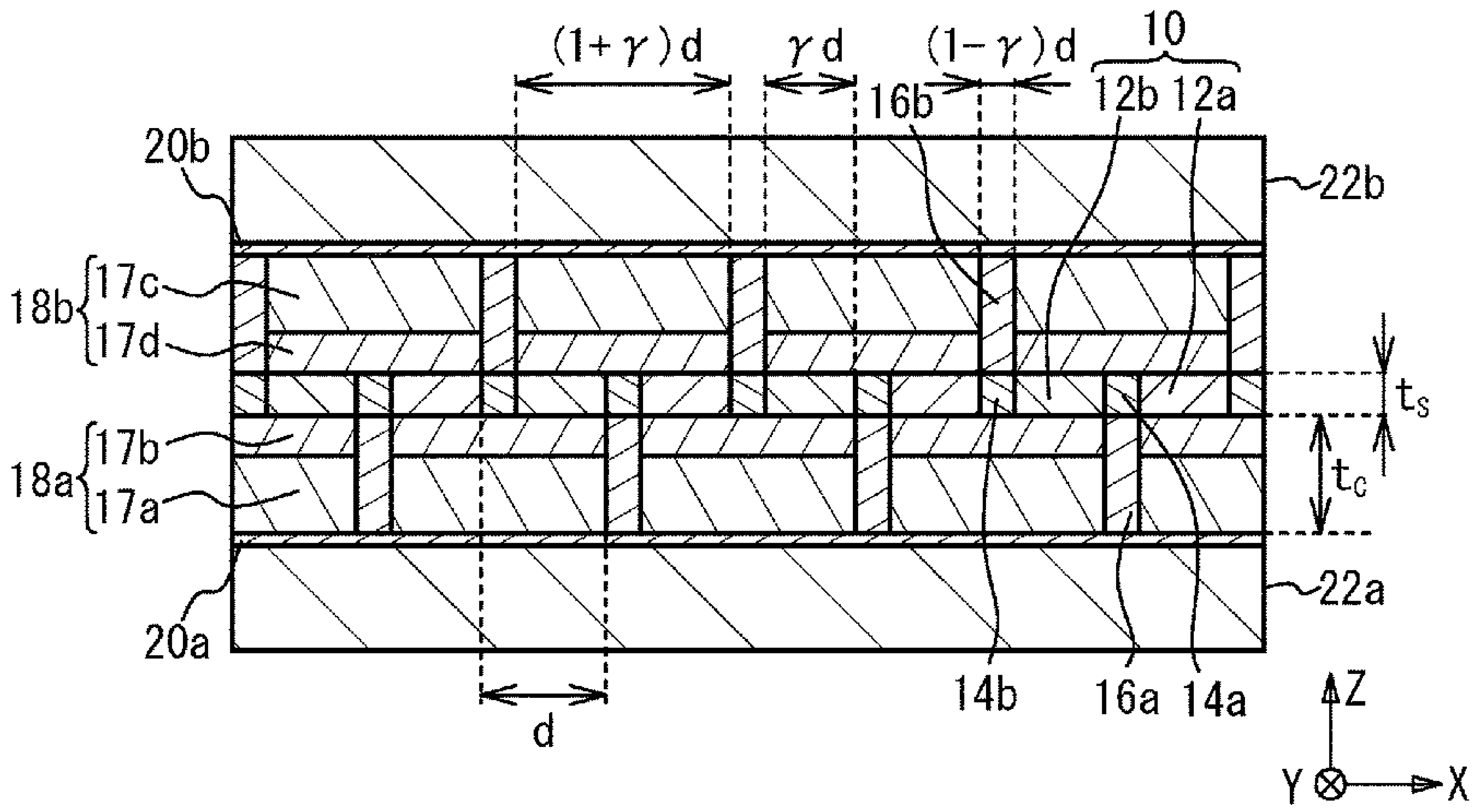

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FIG. 1A

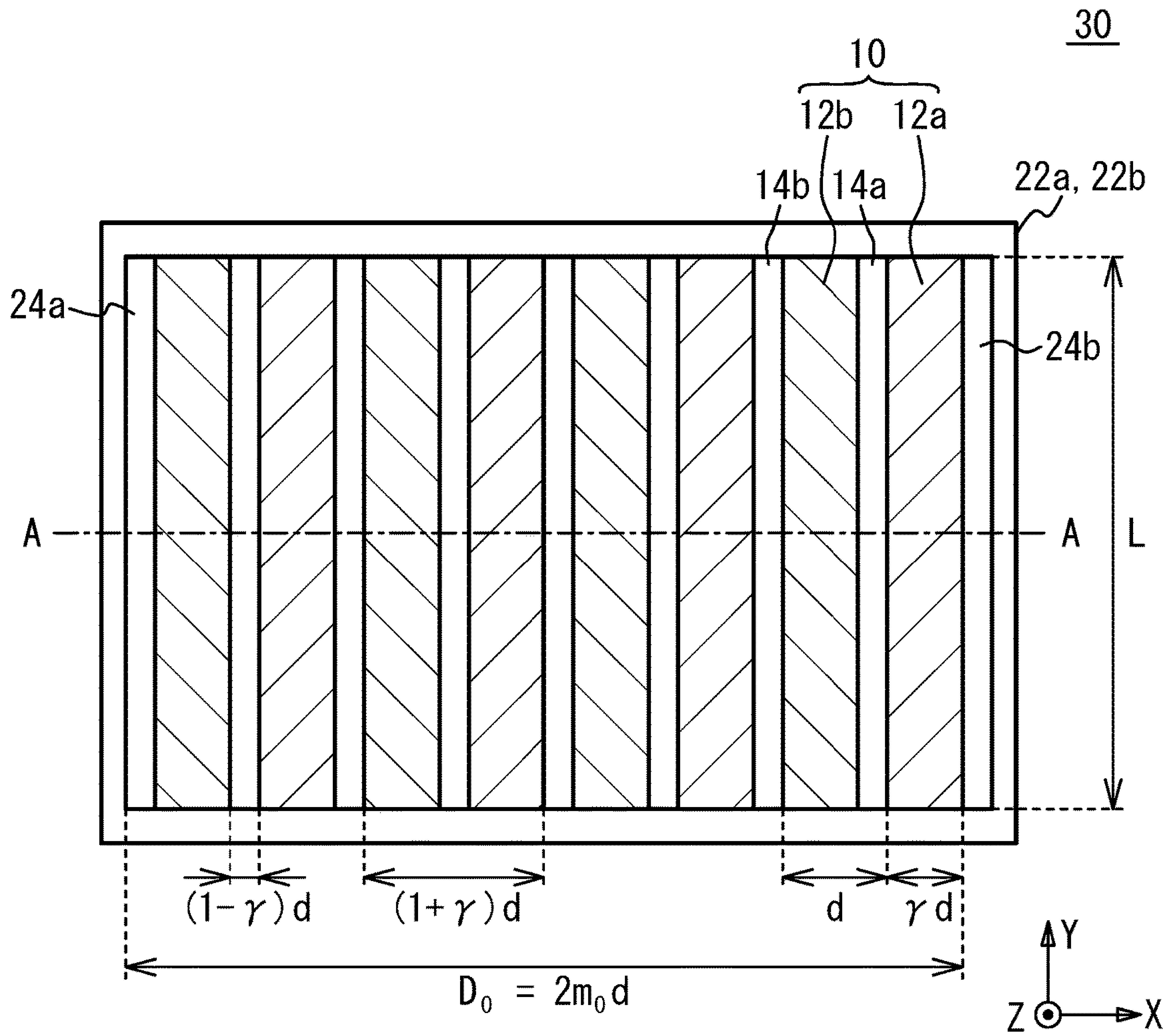
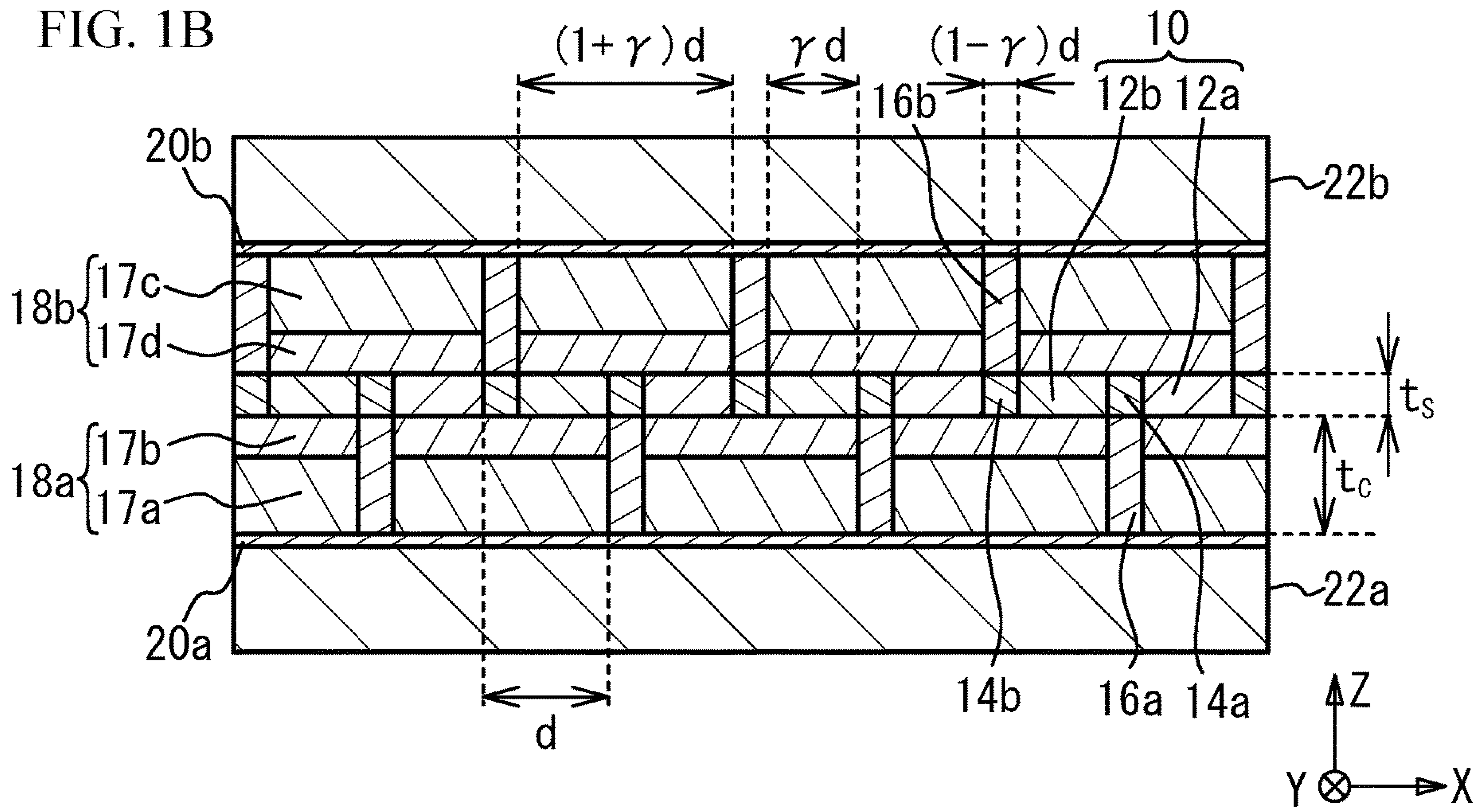

30
10
12b
12a
14b
14a
22a, 22b
24a
24b
A
A
L
(1−γ)d
(1+γ)d
d
γd
D0 = 2m0d
Y
Z
X

FIG. 1B


(1+γ)d
γd
(1−γ)d
10
16b
12b 12a
20b
22b
18b
17c
17d
ts
18a
17b
17a
tc
22a
20a
14b
16a
14a
d
Z
Y
X

[FIG. 2]

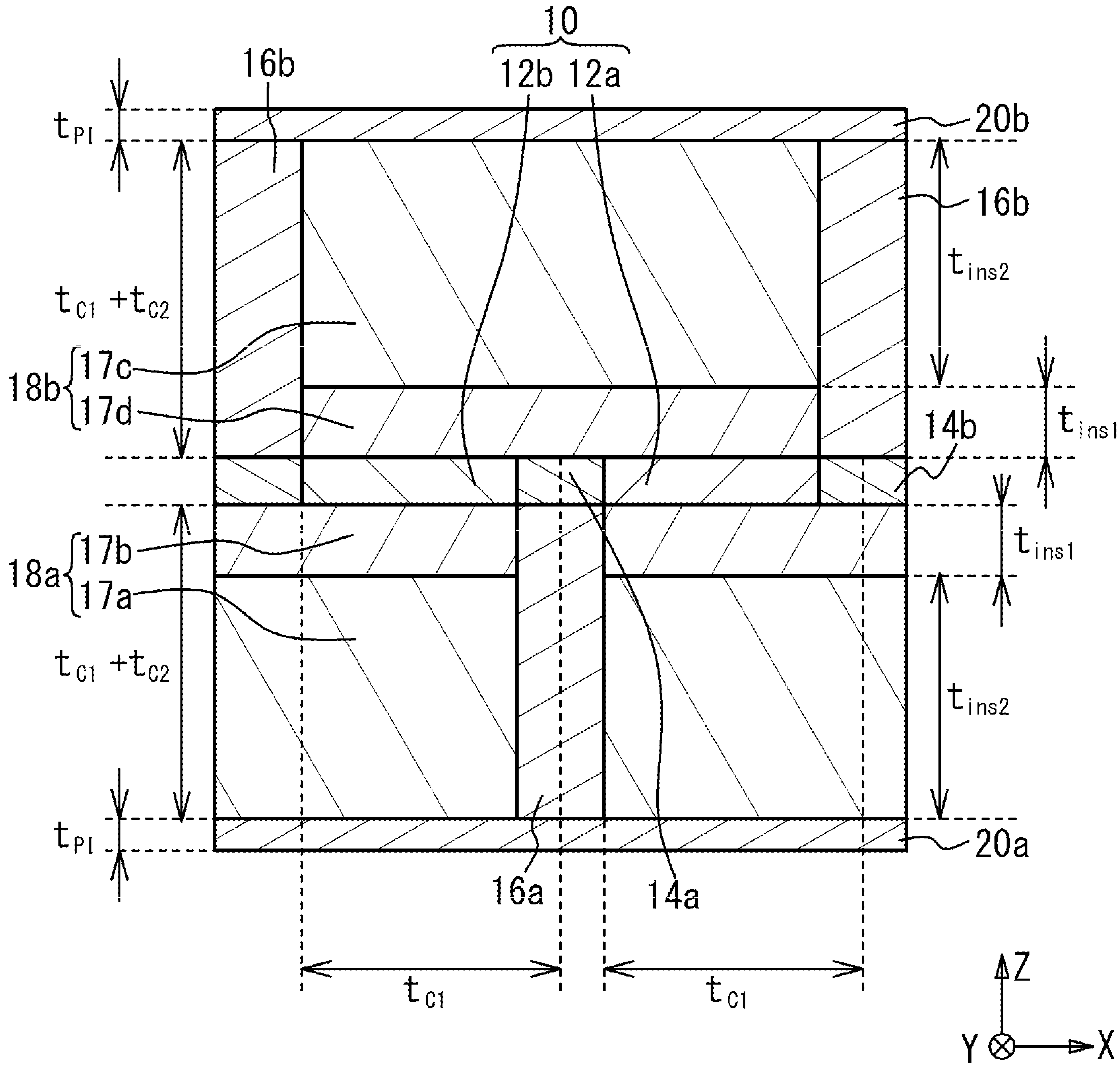
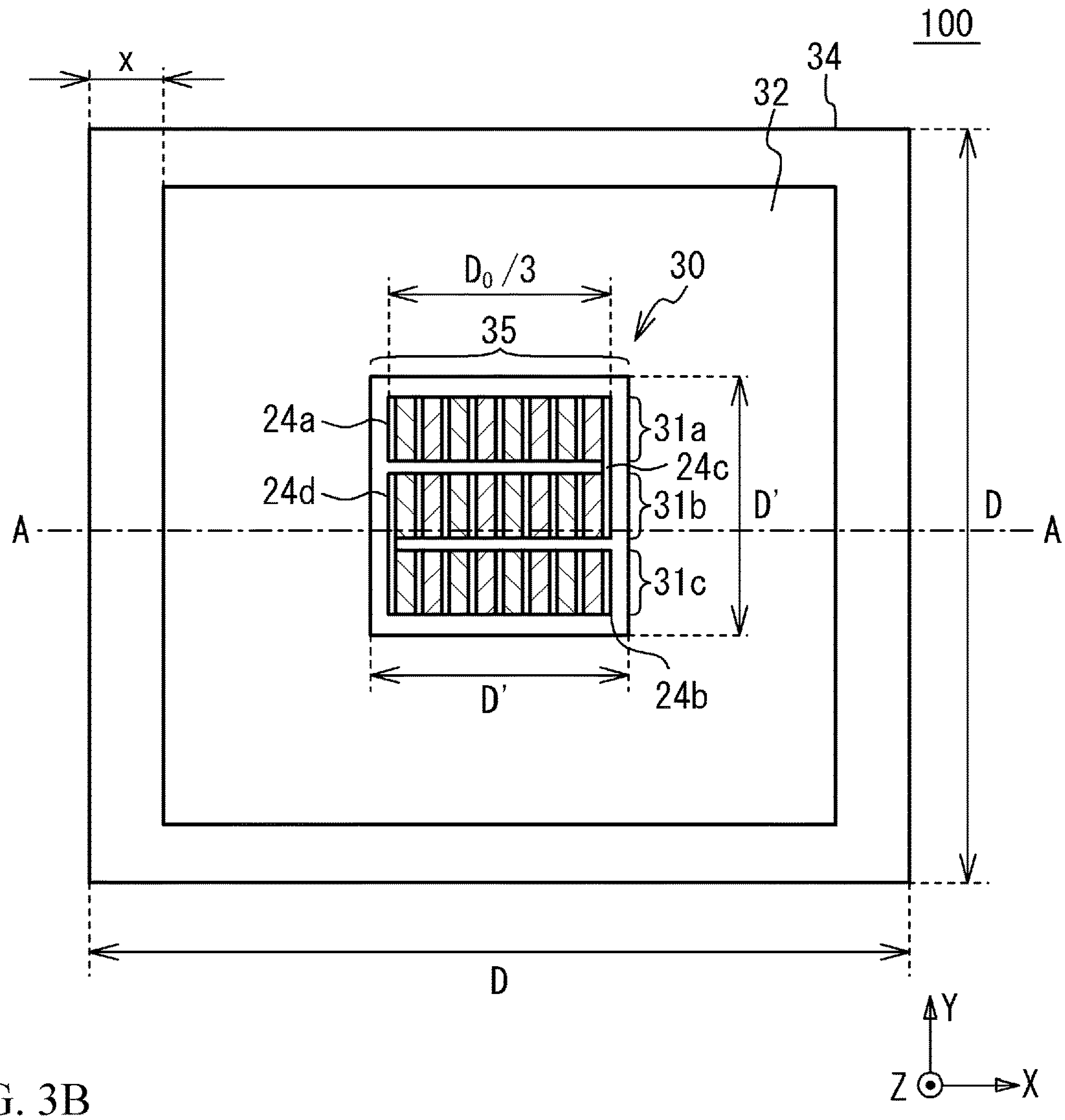
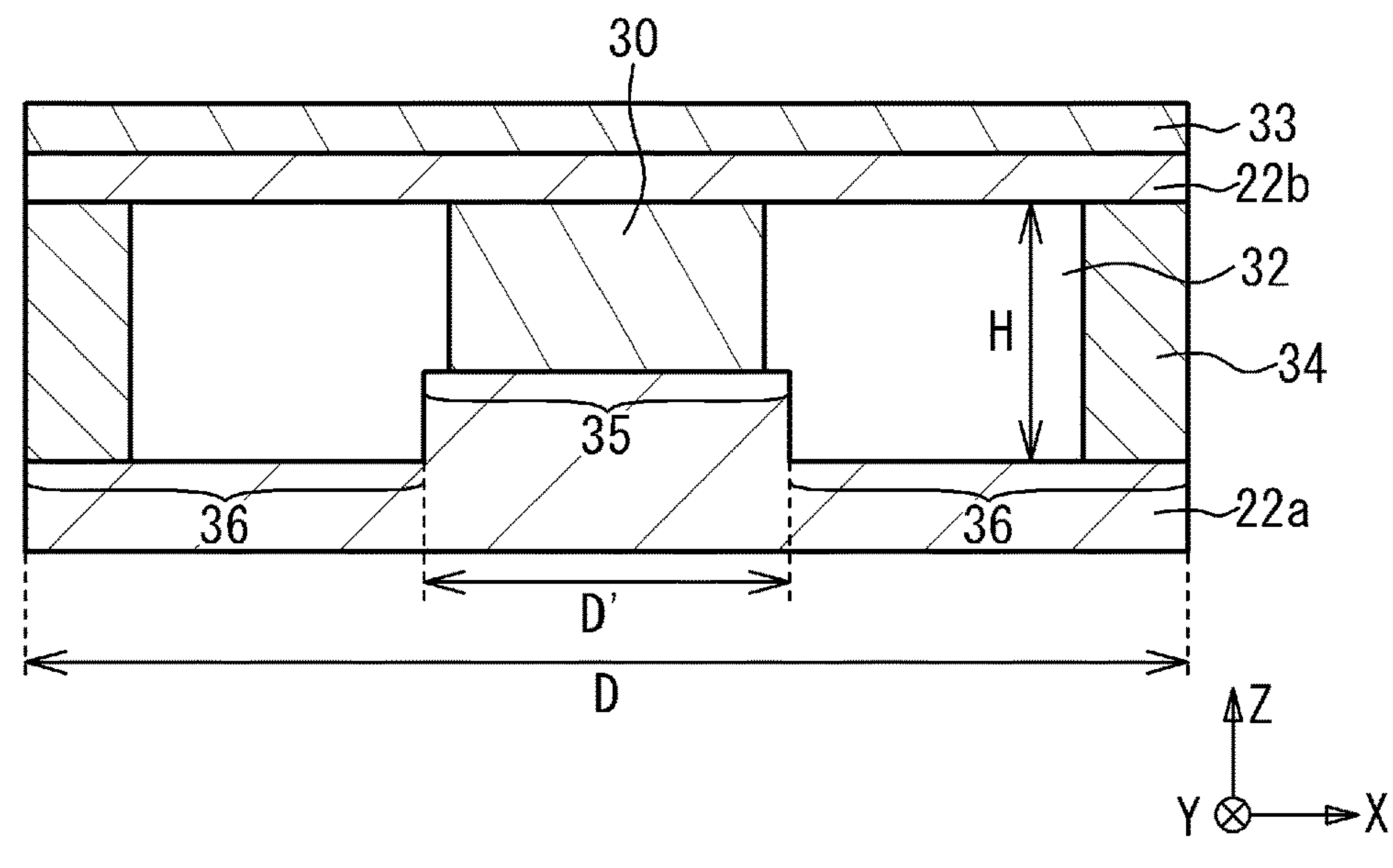

10
12b 12a
16b
20b
16b
t_{PI}
$t_{C1}+t_{C2}$
18b
17c
17d
t_{ins2}
t_{ins1}
14b
t_{ins1}
18a
17b
17a
$t_{C1}+t_{C2}$
t_{ins2}
t_{PI}
20a
16a
14a
t_{C1}
t_{C1}
Z
Y
X

FIG. 3A



100
34
32
x
$D_0/3$
30
35
24a
31a
24c
24d
31b
D'
D
A
A
31c
24b
D'
D
Y
Z
X

FIG. 3B



30
33
22b
32
H
34
35
36
36
22a
D'
D
Z
Y
X

[FIG. 4]

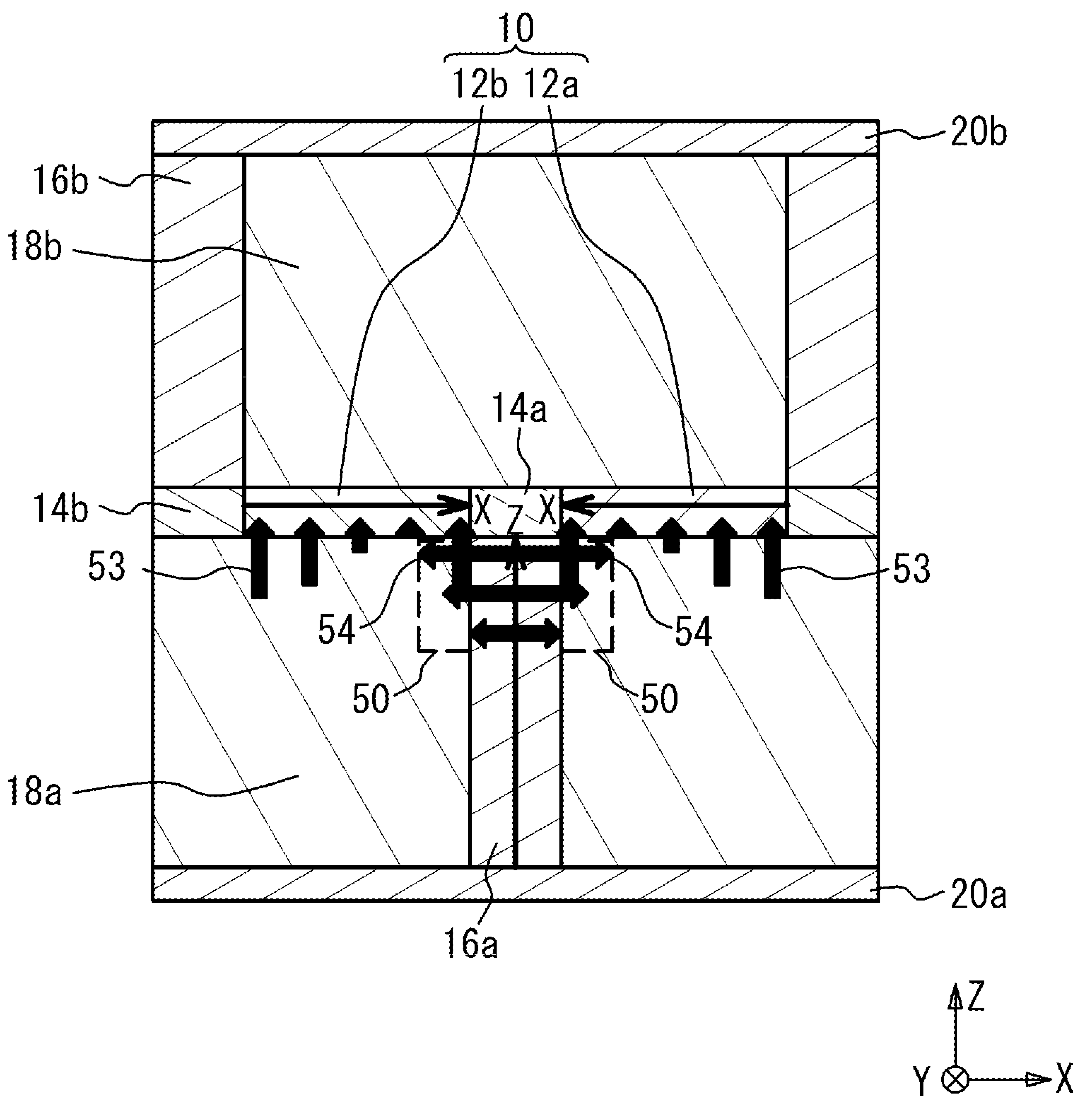

10
12b 12a
20b
16b
18b
14a
14b
X Z X
53
53
54
54
50
50
18a
20a
16a
Z
Y
X

FIG. 5A

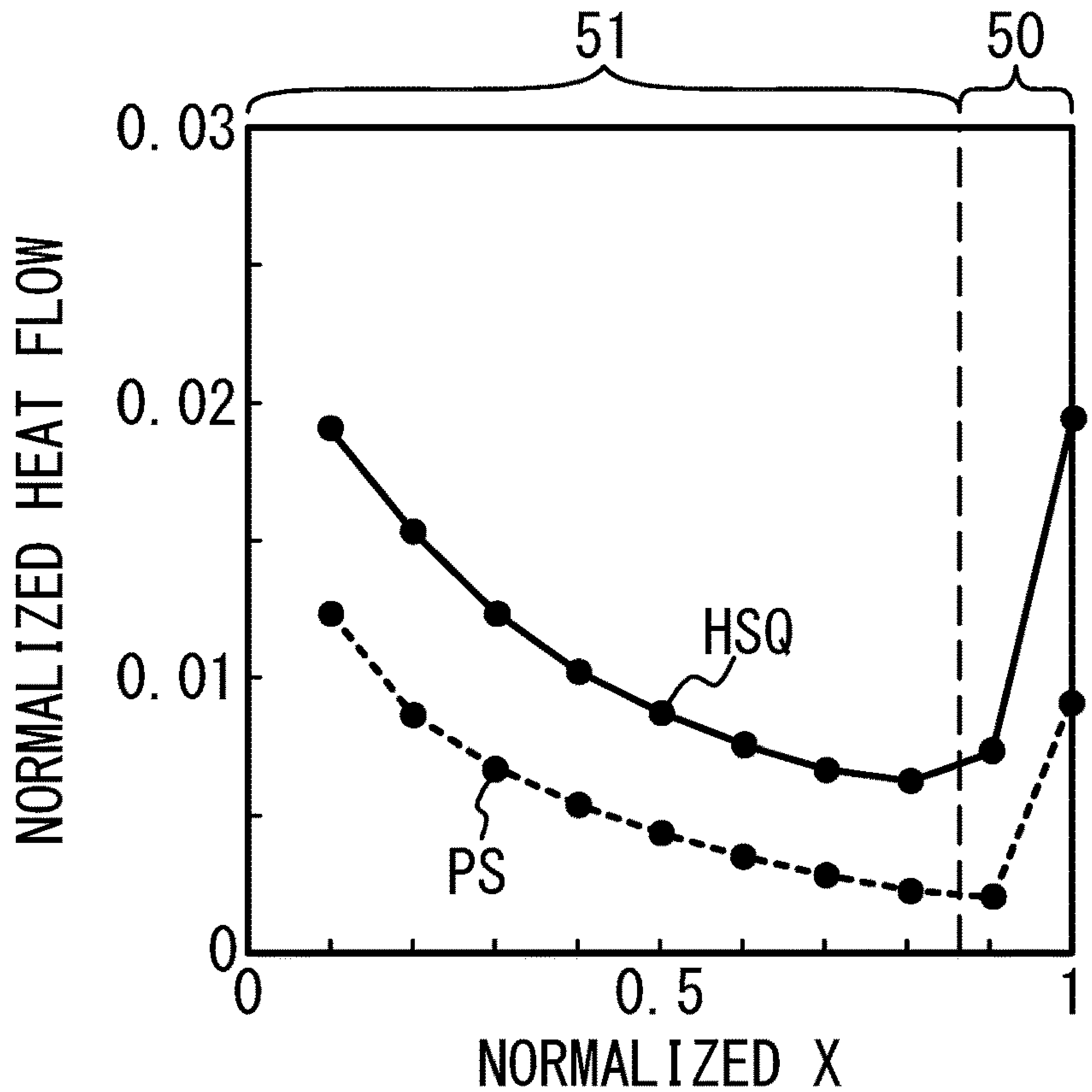
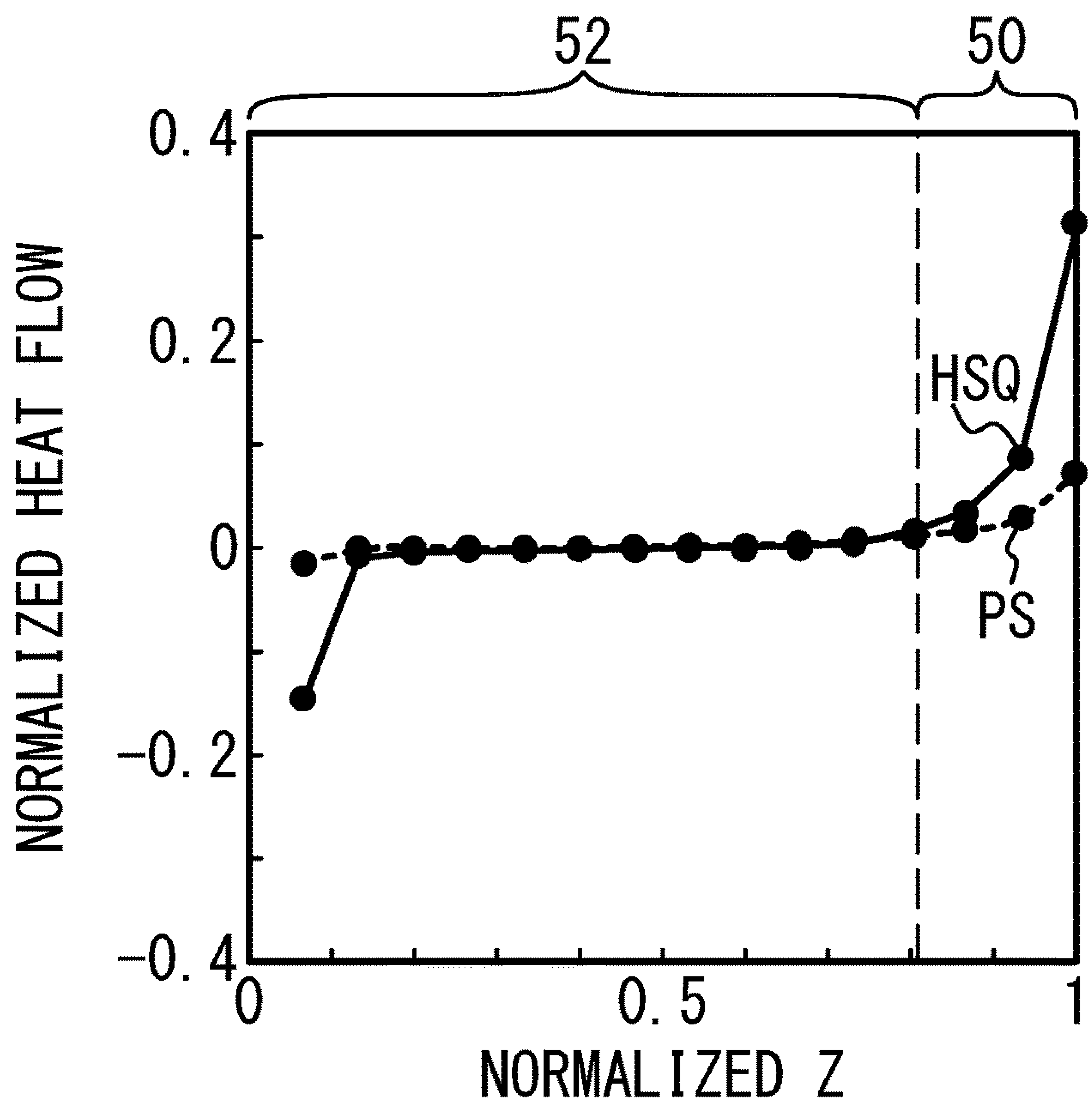

51
50
0.03
0.02
0.01
0
NORMALIZED HEAT FLOW
HSQ
PS
0
0.5
1
NORMALIZED X

FIG. 5B


52
50
0.4
0.2
0
−0.2
−0.4
NORMALIZED HEAT FLOW
HSQ
PS
0
0.5
1
NORMALIZED Z

[FIG. 6]

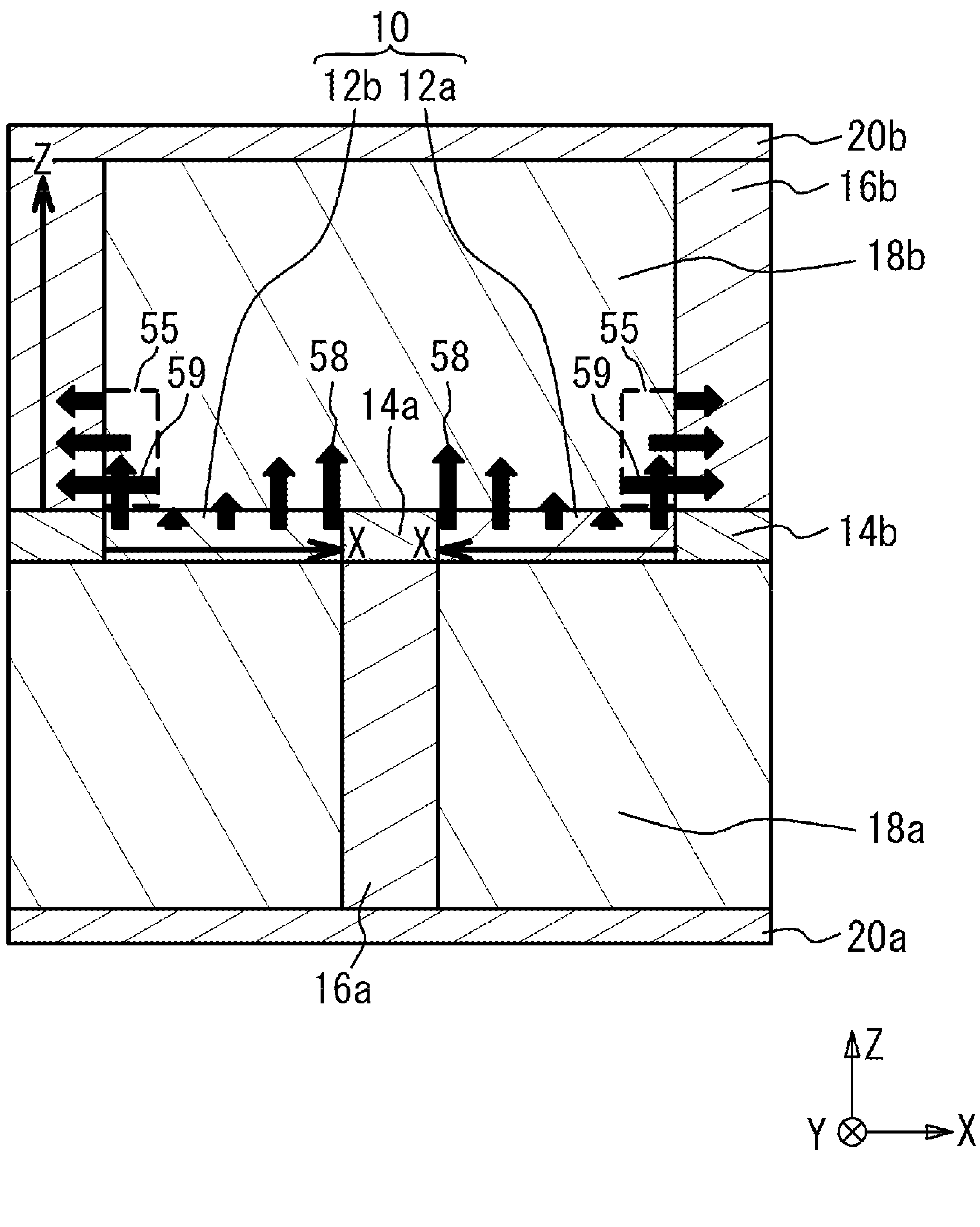

10
12b 12a
20b
16b
18b
Z
55
59
58
58
14a
55
59
X
X
14b
18a
20a
16a
Z
Y
X

FIG. 7A

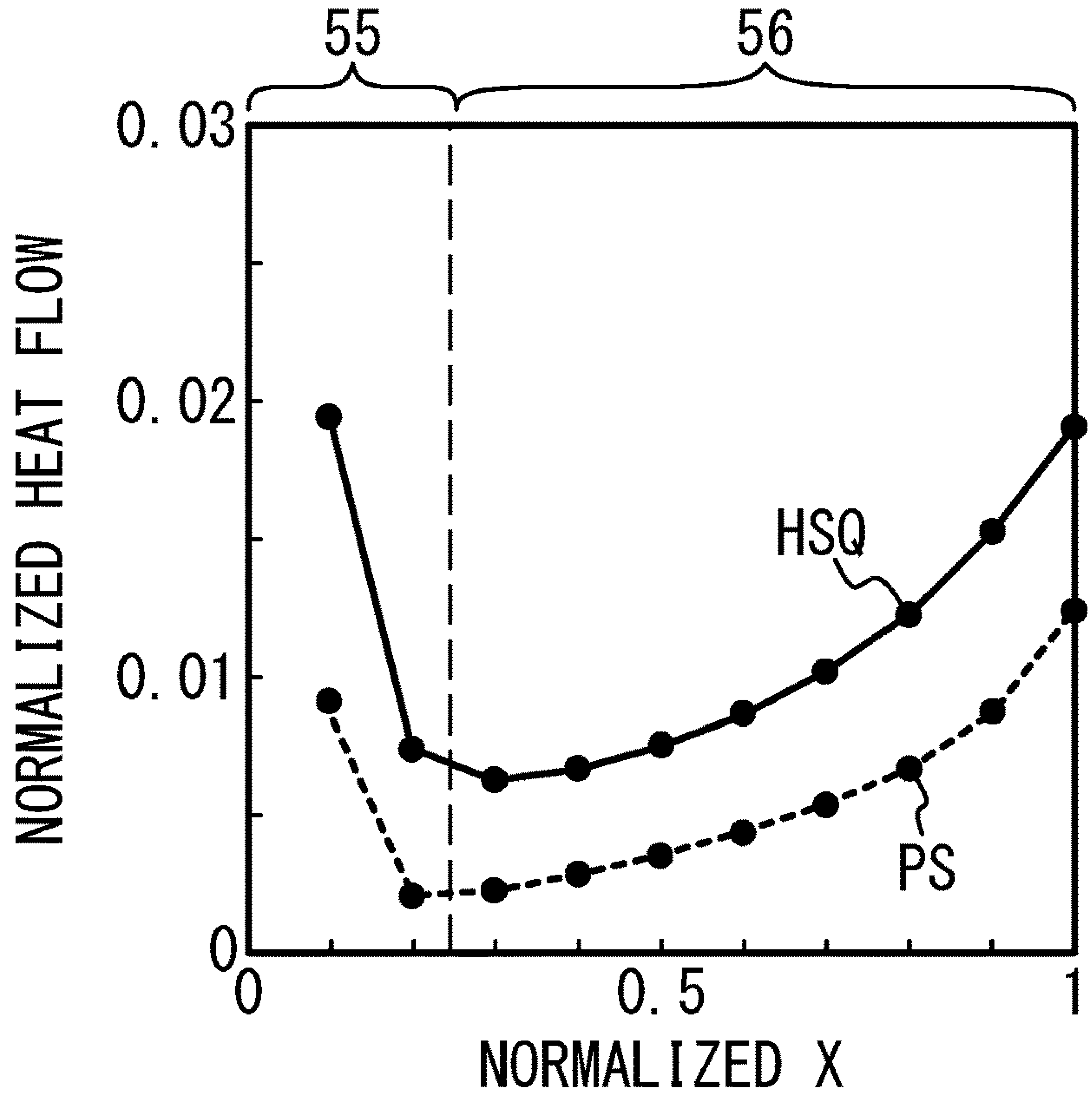

55
56
0.03
0.02
0.01
0
NORMALIZED HEAT FLOW
HSQ
PS
0
0.5
1
NORMALIZED X

FIG. 7B

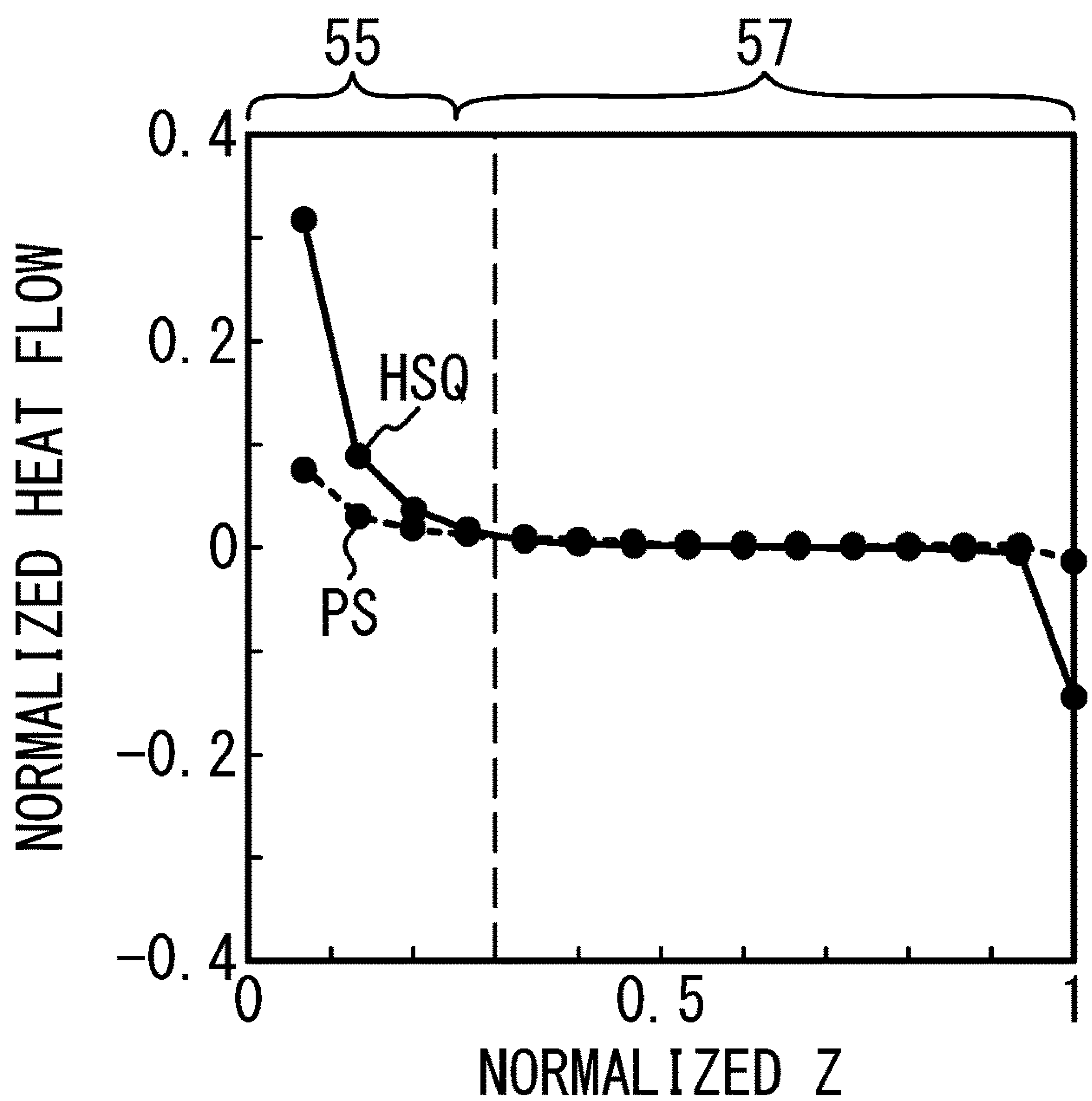

55
57
0.4
0.2
0
−0.2
−0.4
NORMALIZED HEAT FLOW
HSQ
PS
0
0.5
1
NORMALIZED Z

FIG. 8A

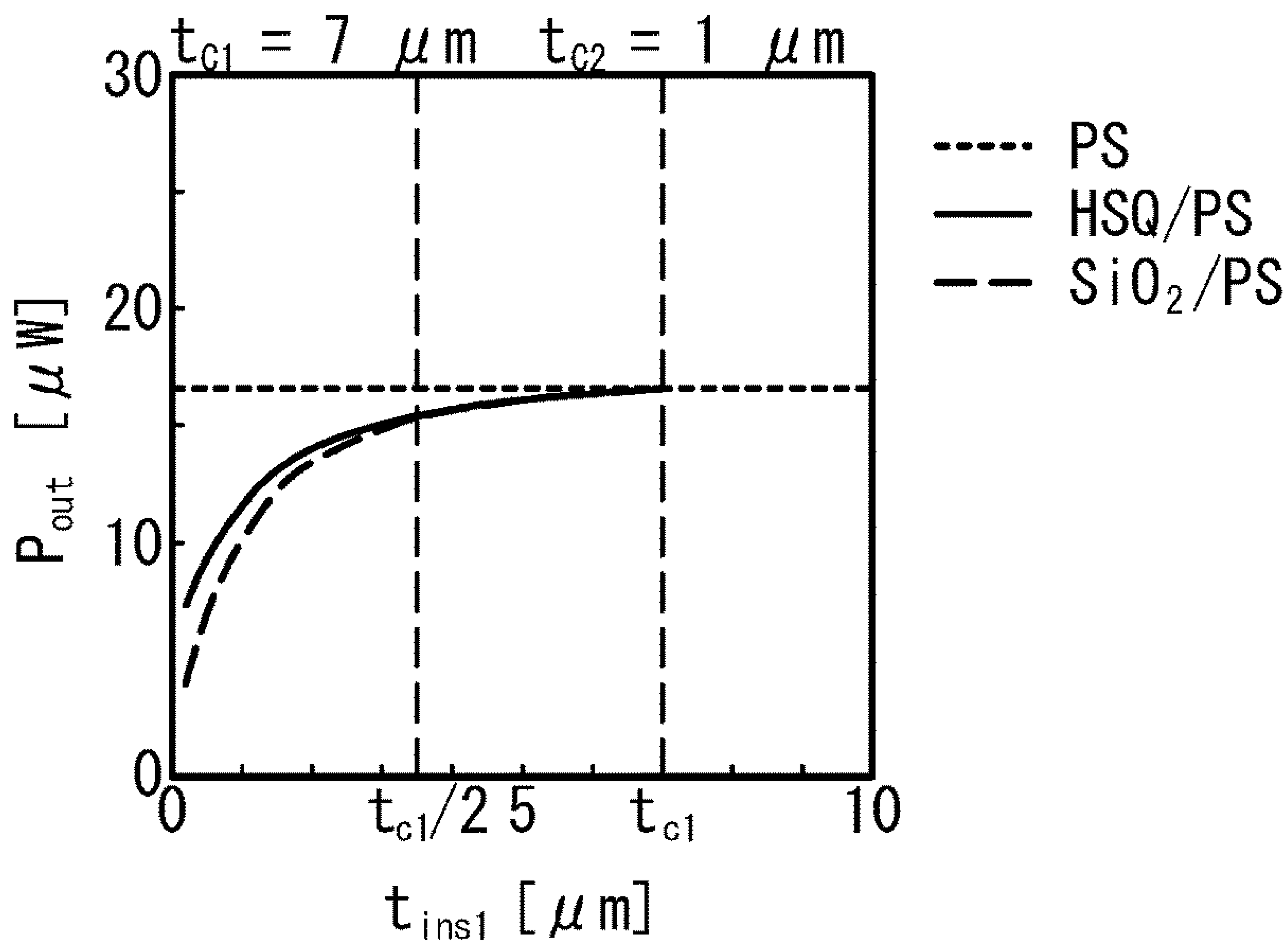


FIG. 8B

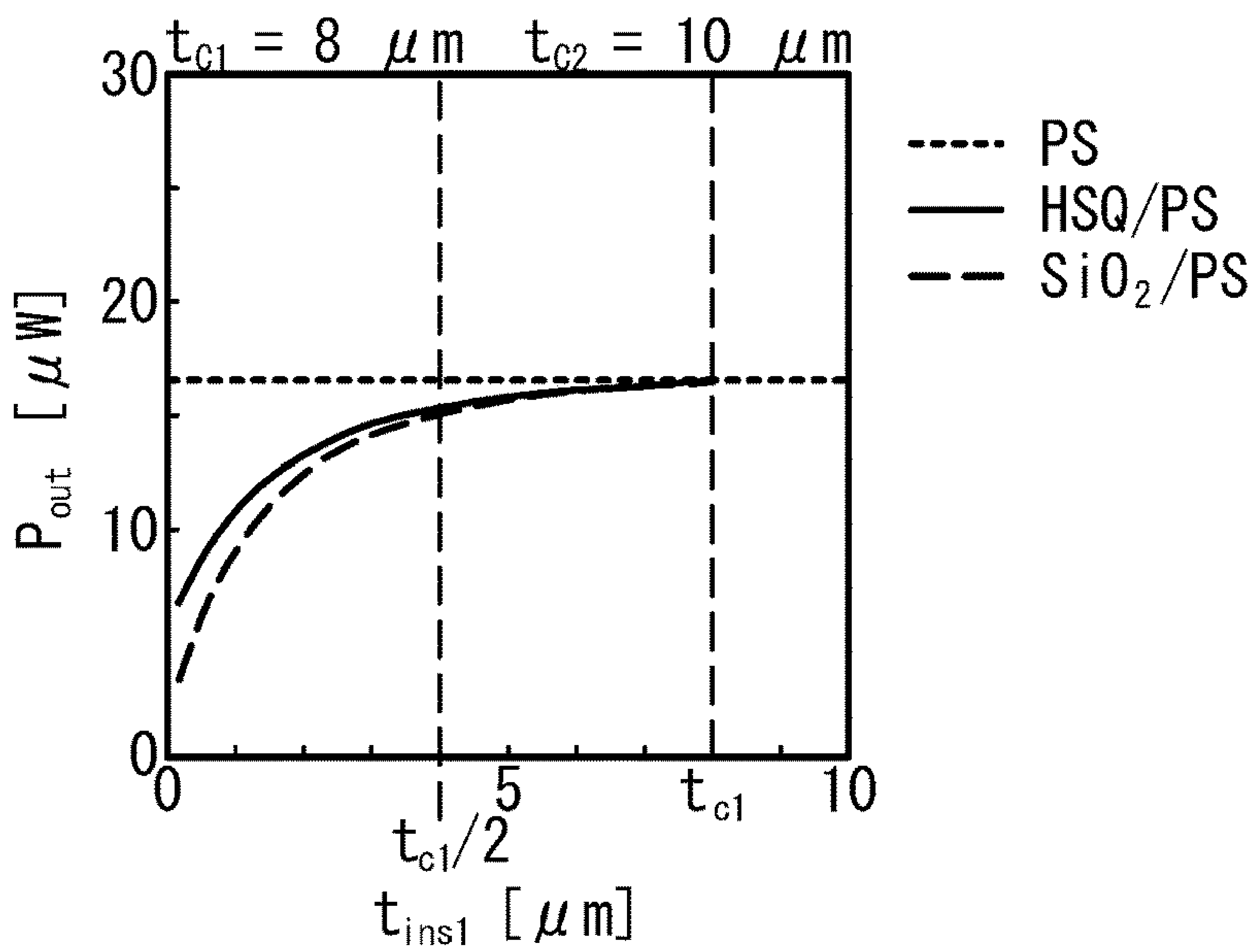


FIG. 8C

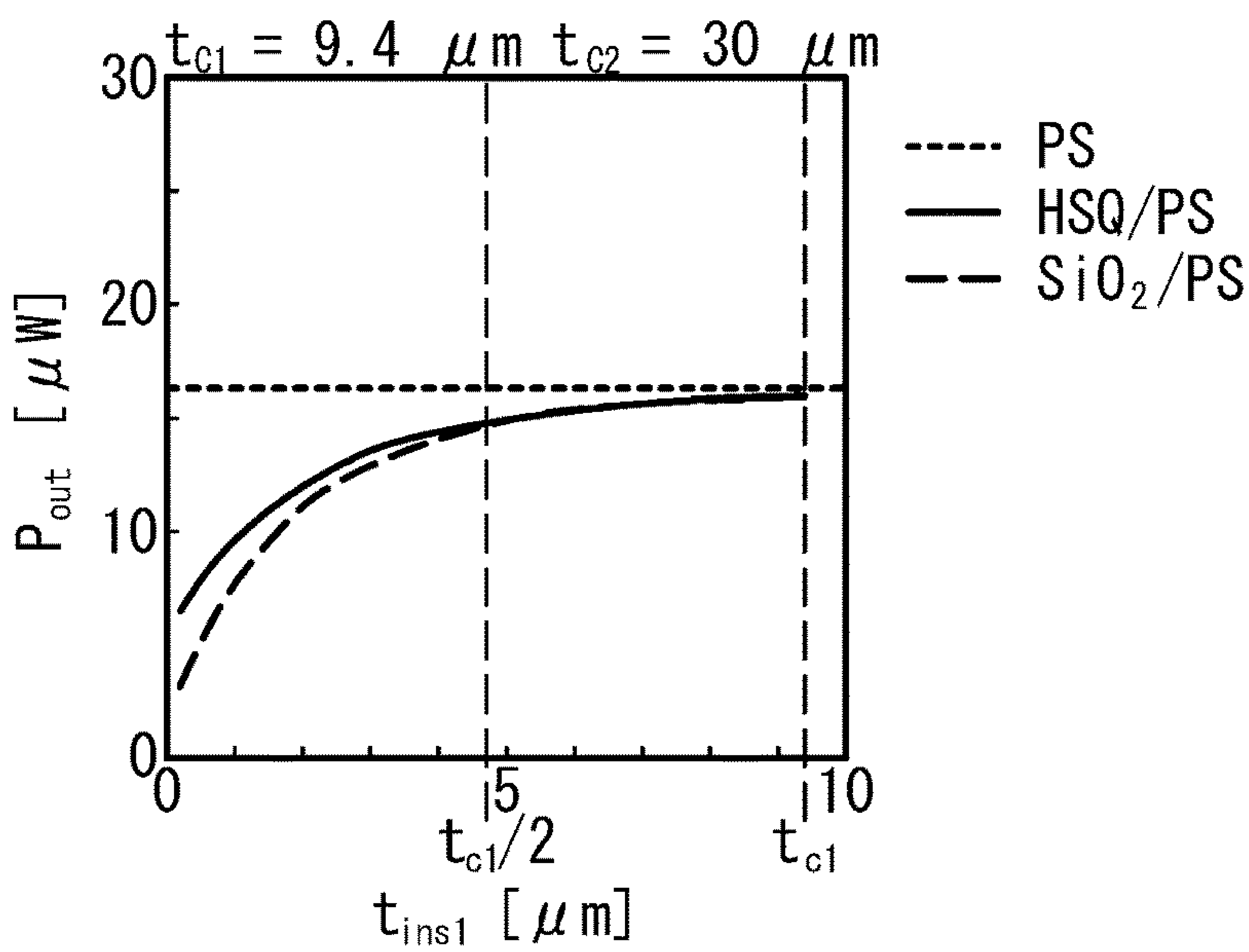


FIG. 9A

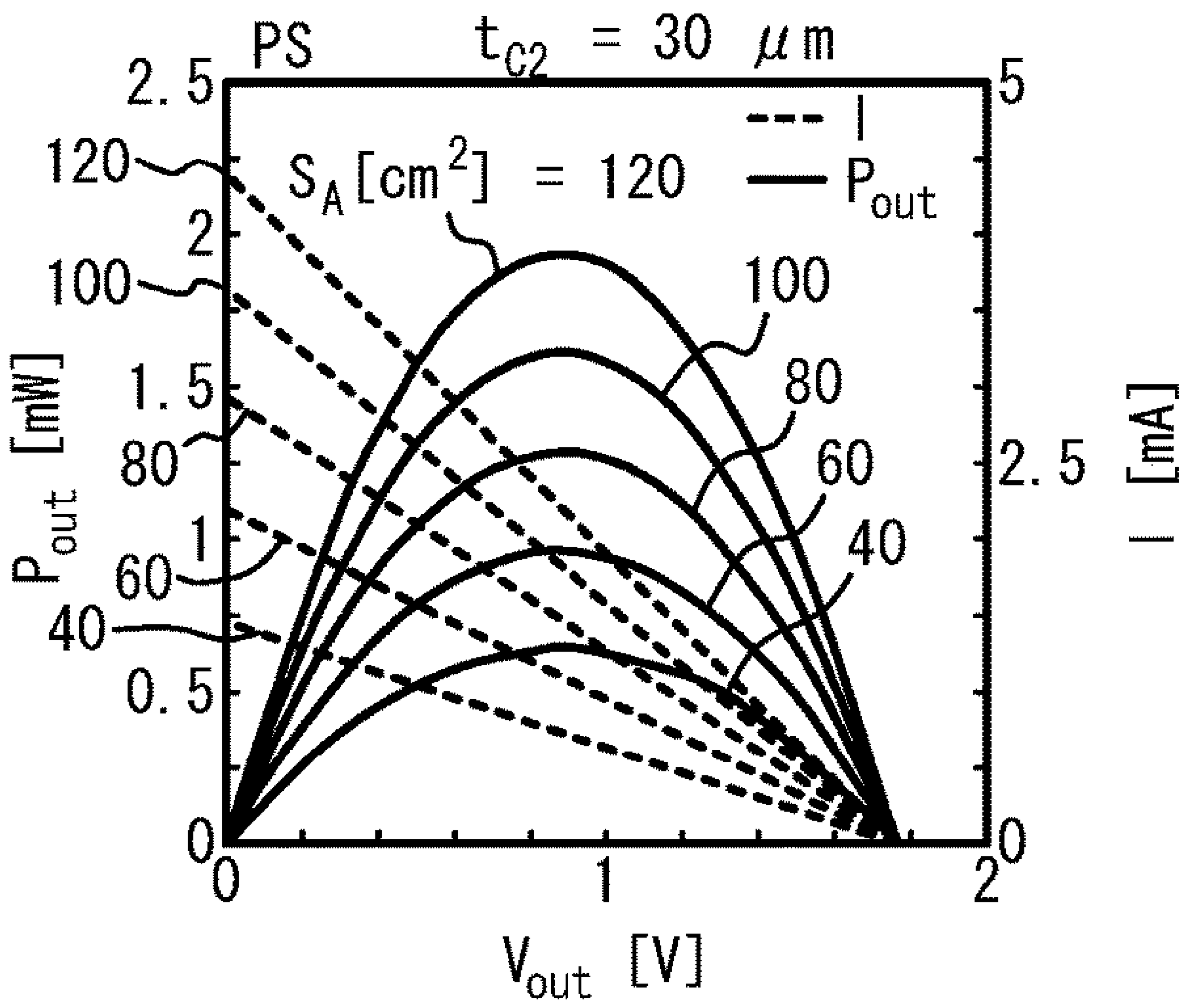


FIG. 9B

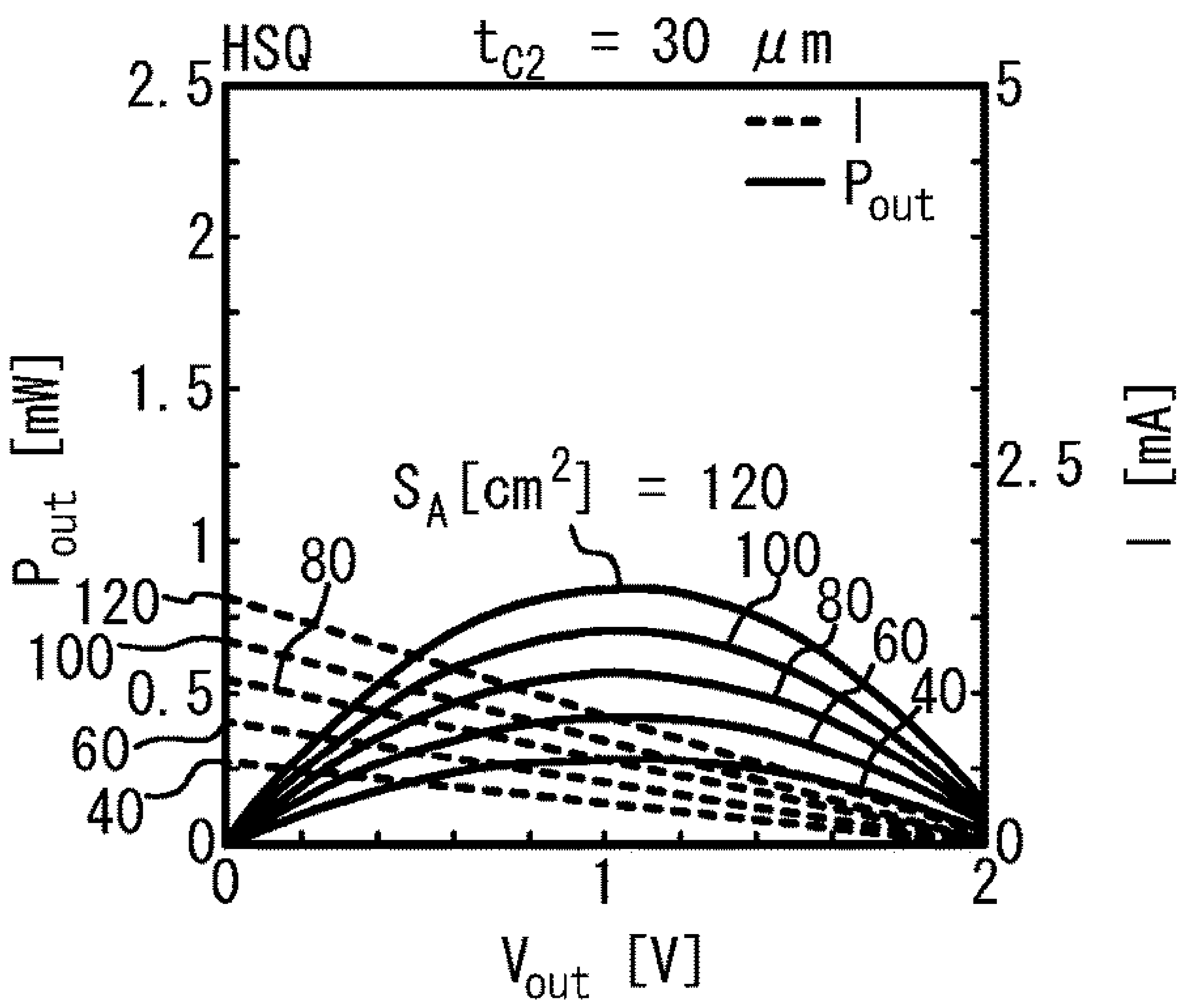


FIG. 9C

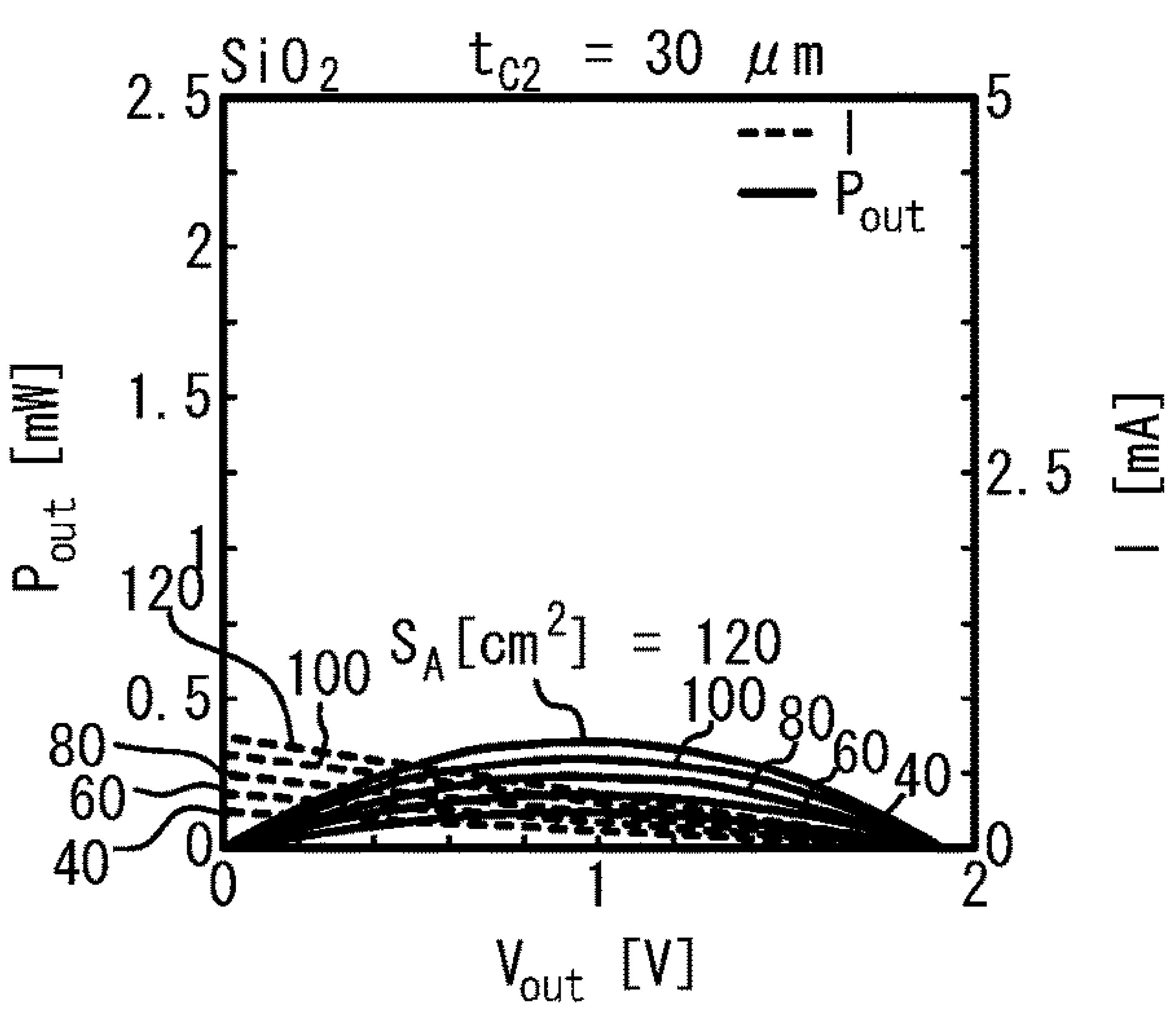


FIG. 9D

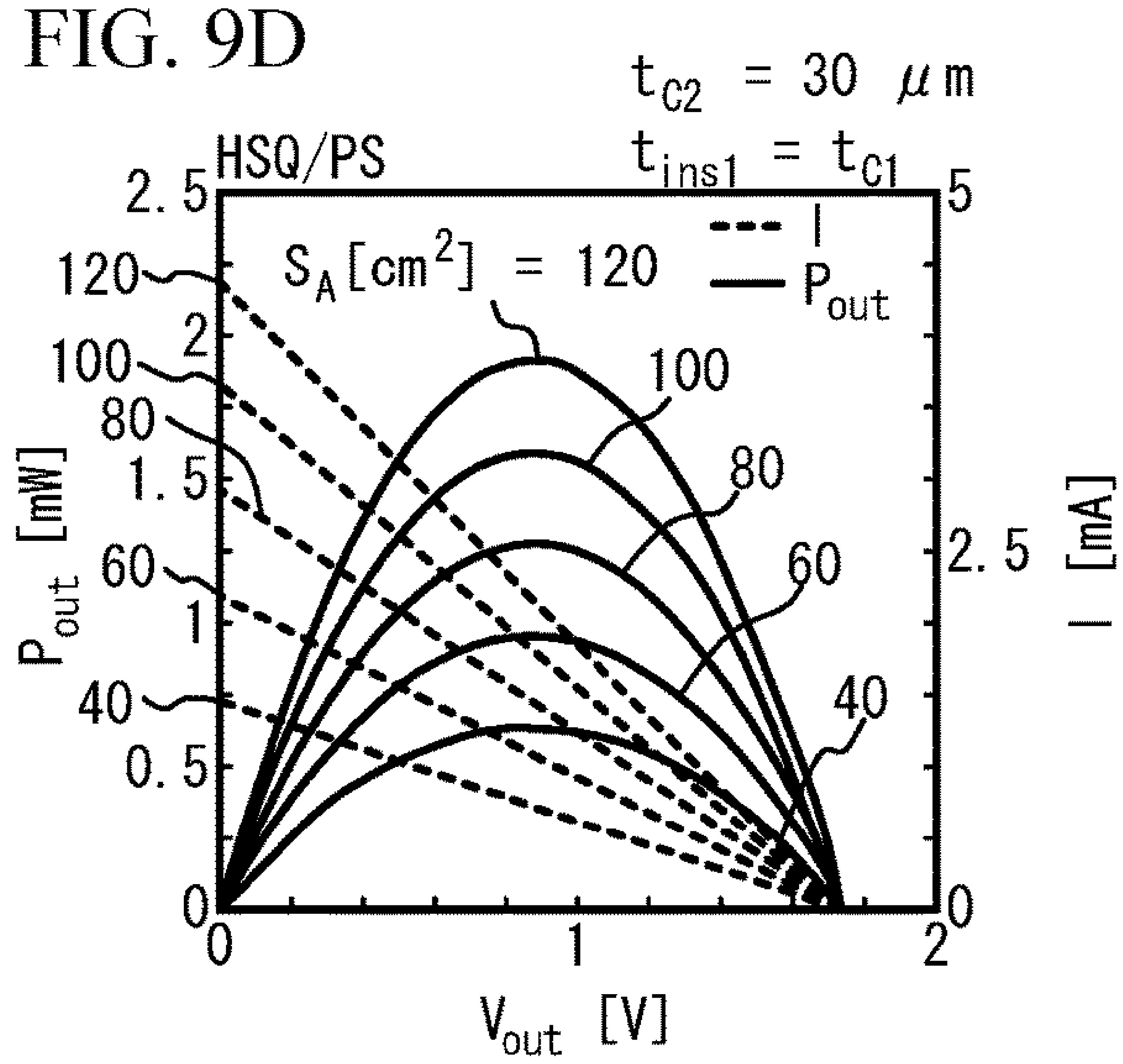
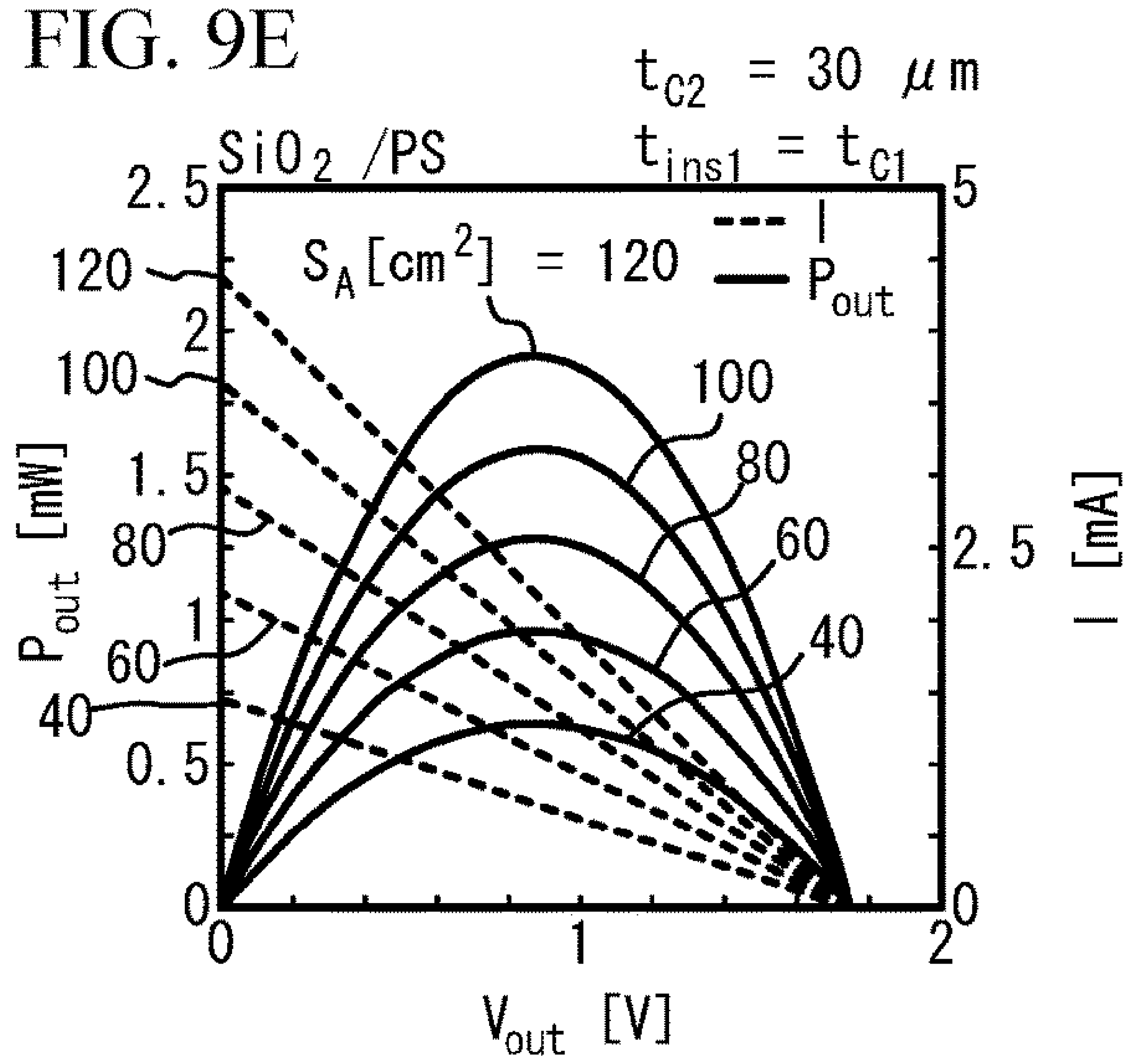
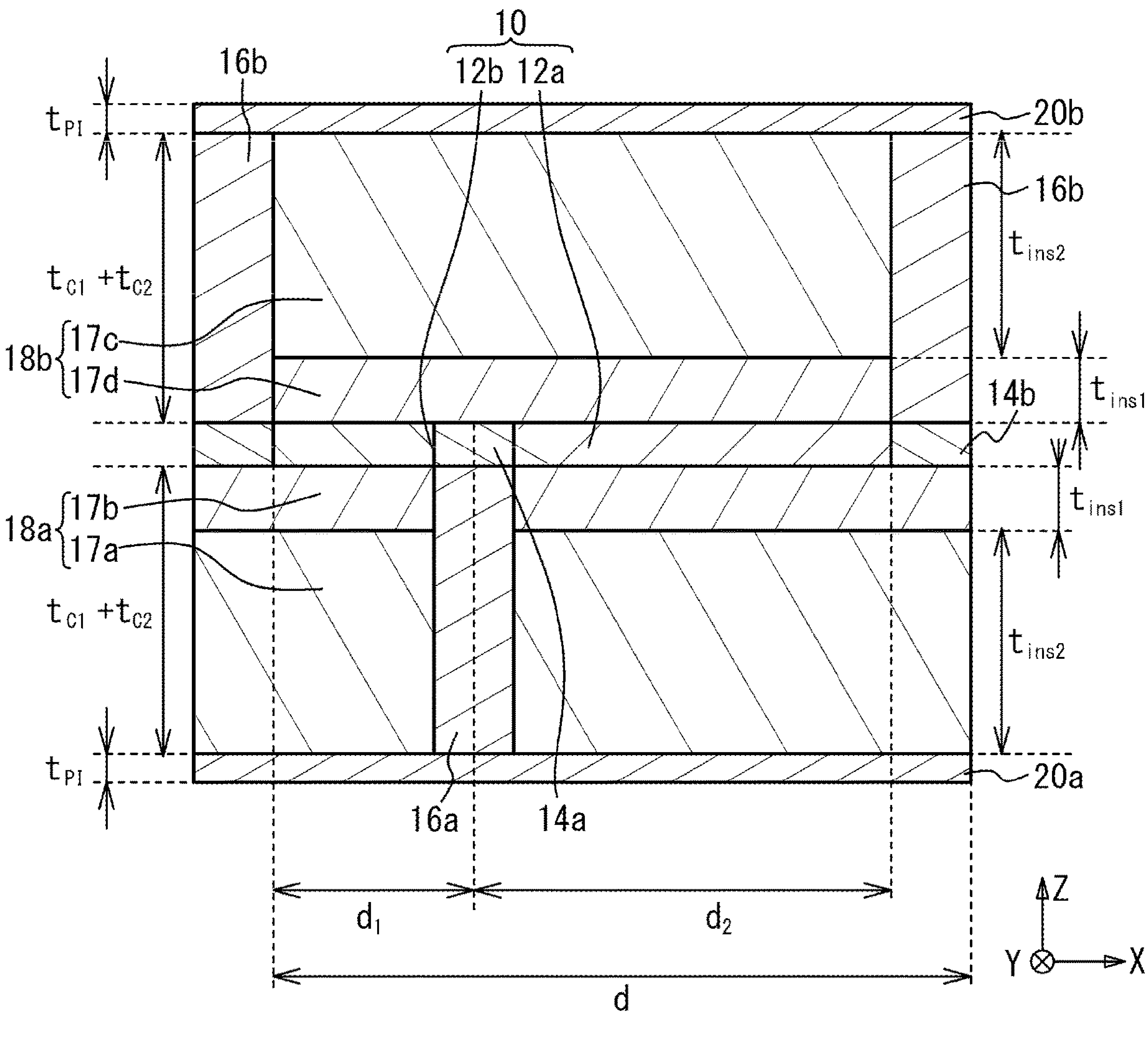


FIG. 9E



[FIG. 10]


10
16b
12b 12a
20b
16b
t_{PI}
$t_{C1}+t_{C2}$
18b
17c
17d
t_{ins2}
t_{ins1}
14b
18a
17b
17a
t_{ins1}
$t_{C1}+t_{C2}$
t_{ins2}
t_{PI}
20a
16a
14a
d_1
d_2
d
Z
Y
X

THERMOELECTRIC CONVERSION DEVICE

TECHNICAL FIELD

The present invention relates to a thermoelectric conversion device.

BACKGROUND ART

There is known a transverse-type μTEG (μTEG: Micro Thermoelectric Generator) in which thermoelectric layers made of a thermoelectric material and connection layers for connecting the thermoelectric layers are alternately arranged in a planar direction, and heat is drawn from the connection layers through a thermally conductive layer in a direction orthogonal to the planar surface (for example, Patent Document 1). The transverse-type μTEG can be applied to thermoelectric power generation using a body temperature with a small temperature difference. It is known to embed an extraction electrode in multilayered insulating layers (a base substrate and a heat insulating substrate) having different thermal conductivities (for example, Patent Document 2).

PRIOR ART DOCUMENT

Patent Document

Patent Document 1: International Publication No. 2018/042708

Patent Document 2: Japanese Patent Application Laid-Open No. 2009-158760

SUMMARY OF THE INVENTION

Problem to be Solved by the Invention

In FIG. 8 of Patent Document 2, thermally-insulating substrates (A2, B2) having high thermal insulating properties are disposed on a side provided with thermoelectric materials (5a to 5h, 6a to 6h) of base substrates (A1, B1). In general, the scale in the planar direction and the scale in the height direction are different from each other in the cross-sectional view of the patents, and Patent Document 2 does not describe the thicknesses of the thermally-insulating substrates (A2, B2). In paragraph 0057 of Patent Document 2, the problem is that the heat flow circumnavigates the thermoelectric materials (5a to 5h, 6a to 6h) between heat-dissipating electrodes (3a to 3i) and heat-absorbing electrodes (2a to 2h, 9a to 8i), which are arranged in the planar direction. When the heat flow in the planar direction is a problem, it is considered that the circumnavigation of the heat flow in the planar direction can be inhibited even if the thermally-insulating substrates (A2, B2) are thin. However, the heat flow circumnavigating the thermoelectric materials (5a to 5h, 6a to 6h) cannot be reduced by simply taking the heat flow in the planar direction into consideration, which results in decrease in the output power of the thermoelectric conversion device.

The present invention has been made in view of the above problems, and an object thereof is to provide a thermoelectric conversion device having large output power.

Means for Solving the Problem

The present invention is a thermoelectric conversion device including: first thermoelectric layers and second thermoelectric layers that are alternately provided in a first direction parallel to surfaces of the first thermoelectric layers and the second thermoelectric layers, the first thermoelectric layers having conductivity types opposite to those of the second thermoelectric layers; first connection layers and second connection layers that are electrically and thermally connected to the first thermoelectric layers and the second thermoelectric layers between the first thermoelectric layers and the second thermoelectric layers, the first connection layers and the second connection layers being alternately provided in the first direction; first thermally conductive layers that are thermally connected to the first connection layers, the first thermally conductive layers extending in a second direction intersecting the surfaces; a first insulating layer through which the first thermally conductive layers penetrate, the first insulating layer having a thermal conductivity smaller than thermal conductivities of the first thermally conductive layers; a second insulating layer through which the first thermally conductive layers penetrate, the second insulating layer having a thermal conductivity smaller than the thermal conductivity of the first insulating layer, the second insulating layer being provided between the first insulating layer and the first thermoelectric layers and the second thermoelectric layers, the second insulating layer having a thickness equal to or greater than ¼ of a larger distance of a distance between an end of the first thermally conductive layer at a side of the first thermoelectric layer and a center of the second connection layer in the first direction and a distance between an end of the first thermally conductive layer at a side of the second thermoelectric layer and the center of the second connection layer in the first direction.

In the above configuration, a configuration in which provided are: second thermally conductive layers that are thermally connected to the second connection layers, the second thermally conductive layers being provided at a side opposite to the first thermally conductive layers with respect to the first thermoelectric layers and the second thermoelectric layers, the second thermally conductive layers extending in the second direction; a third insulating layer through which the second thermally conductive layers penetrate, the third insulating layer having a thermal conductivity smaller than thermal conductivities of the second thermally conductive layers; and a fourth insulating layer through which the second thermally conductive layers penetrate, the fourth insulating layer having a thermal conductivity smaller than the thermal conductivity of the third insulating layer, the fourth insulating layer being provided between the third insulating layer and the first thermoelectric layers and the second thermoelectric layers, the fourth insulating layer having a thickness equal to or greater than ¼ of the larger distance may be employed.

In the above configuration, a configuration in which the thickness of the second insulating layer is equal to or less than twice the larger distance may be employed.

In the above configuration, a configuration in which a thickness of the first insulating layer is equal to or greater than ½ of the thickness of the second insulating layer may be employed.

In the above configuration, a configuration in which the second insulating layer is porous, and the first insulating layer is non-porous may be employed.

In the above configuration, a configuration in which the second insulating layer is in contact with the first thermoelectric layers and the second thermoelectric layers, and is in contact with the first insulating layer may be employed.

In the above configuration, a configuration in which the fourth insulating layer is porous, and the third insulating layer is non-porous may be employed.

In the above configuration, a configuration in which the fourth insulating layer is in contact with the first thermoelectric layers and the second thermoelectric layers, and is in contact with the third insulating layer may be employed.

In the above configuration, a configuration in which the second insulating layer is in contact with the first thermoelectric layers and the second thermoelectric layers, and is in contact with the first insulating layer, the thickness of the second insulating layer is equal to or less than twice the larger distance, and the thickness of the fourth insulating layer is equal to or less than twice the larger distance may be employed.

In the above configuration, a configuration in which the thermal conductivity of the second insulating layer and the thermal conductivity of the fourth insulating layer are equal to or less than ⅕ times and equal to or greater than 1/100 times a thermal conductivity of the first insulating layer and a thermal conductivity of the second insulating layer may be employed.

In the above configuration, a configuration in which the thermal conductivity of the second insulating layer and the thermal conductivity of the fourth insulating layer are equal to or less than 1/300 times and equal to or greater than 1/30000 times the thermal conductivities of the first connection layer, the second connection layer, the first thermally conductive layer, and the second thermally conductive layer may be employed.

In the above configuration, a configuration in which the thermal conductivities of the first thermoelectric layers and the second thermoelectric layers are equal to or less than 1/50 times the thermal conductivities of the first connection layers, the second connection layers, the first thermally conductive layers, and the second thermally conductive layers may be provided.

In the above configuration, a configuration in which the thermal conductivities of the first thermoelectric layers and the second thermoelectric layer are greater than the thermal conductivities of the second insulating layer and the fourth insulating layer may be employed.

In the above configuration, a configuration in which the first insulating layer and the third insulating layer are HSQ layers or silicon oxide layers, and the second insulating layer and the fourth insulating layer are porous silica may be employed.

In the above configuration, a configuration in which the distance between the end of the first thermally conductive layer at the side of the first thermoelectric layer and the center of the second connection layer in the first direction is the same as the distance between the end of the first thermally conductive layer at the side of the second thermoelectric layer and the center of the second connection layer in the first direction may be employed.

Effects of the Invention

The present invention can provide a thermoelectric conversion device having large output power.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A is a plan view of a thermoelectric conversion device in accordance with a first embodiment, and FIG. **1**B is a cross-sectional view taken along line A-A in FIG. **1**A.

FIG. **2** is an enlarged cross-sectional view of the thermoelectric conversion device in accordance with the first embodiment.

FIG. **3**A is a plan view of a thermoelectric conversion module in accordance with the first embodiment, and FIG. **3**B is a cross-sectional view taken along line A-A in FIG. **3**A.

FIG. **4** illustrates heat flow in a comparative example 1.

FIG. **5**A and FIG. **5**B are graphs presenting normalized heat flow versus normalized X and normalized Z, respectively.

FIG. **6** illustrates heat flow in the comparative example 1.

FIG. **7**A and FIG. **7**B are graphs presenting normalized heat flow versus normalized X and normalized Z, respectively.

FIG. **8**A to FIG. **8**C are graphs presenting P_{out} versus t_{ins1} in the first embodiment.

FIG. **9**A to FIG. **9**E are graphs presenting current I and output power P_{out} versus output voltage V_{out} in respective samples.

FIG. **10** is an enlarged cross-sectional view of a thermoelectric conversion device in accordance with a first variation of the first embodiment.

MODES FOR CARRYING OUT THE INVENTION

FIG. 8 of Patent Document 2 does not describe the thicknesses of the thermally-insulating substrates (A2, B2) as described above. If the thermally-insulating substrates (A2, B2) having a low mechanical strength are thick, the mechanical strength of the thermoelectric conversion device is low. If the thermally insulating substrates (A2, B2) are thin, the thermoelectric conversion device is deteriorated in performances. In addition, in FIG. 8 of Patent Document 2, spaces 15 (that is, air gaps) are provided between the thermoelectric materials (5a to 5h, 6a to 6h) and the thermally-insulating substrate (B2). Air gaps provided between the thermoelectric material and the thermally-insulating substrate reduce the strength of the thermoelectric conversion device.

Therefore, a thermoelectric conversion device having no air gap was simulated by using a highly accurate distributed constant circuit model developed by the inventors. The distributed constant circuit model allows for highly accurate simulations by taking into account the thermal conductivity of each material. The simulation results has revealed, for the first time, a structure that can reduce degradation in performances such as output power while ensuring mechanical strength. Embodiments and simulation results thereof will be described below.

First Embodiment

FIG. **1**A is a plan view of a thermoelectric conversion device in a first embodiment, and FIG. **1**B is a cross-sectional view taken along line A-A in FIG. **1**A. FIG. **2** is an enlarged cross-sectional view of the thermoelectric conversion device in the first embodiment. In FIG. **1**A, thermoelectric layers, connection layers, and electrodes are illustrated. The surfaces of thermoelectric layers **12***a* and **12***b* are defined as an XY plane, the arrangement direction (widthwise direction) and the extending direction (lengthwise direction) of the thermoelectric layers **12***a* and **12***b* are defined as an X direction and a Y direction, respectively, and the stacking method of the layers is defined as a Z direction.

As illustrated in FIG. **1**A, FIG. **1**B, and FIG. **2**, in a thermoelectric conversion device **30**, the thermoelectric layer **12***a* (a first thermoelectric layer) and the thermoelectric layer **12***b* (a second thermoelectric layer) have a strip shape extending in the Y direction. The thermoelectric layers **12***a* and **12***b* are alternately disposed in the X direction (a first direction parallel to the surfaces). The thermoelectric layers **12***a* and **12***b* are n-type and p-type, respectively, and have conductivity types opposite to each other. Adjacent thermoelectric layers **12***a* and **12***b* are alternately electrically and thermally connected to connection layers **14***a* (a first connection layer) and **14***b* (a second connection layer) in the X-direction. The connection layers **14***a* and **14***b* extend in the Y direction. A pair of the thermoelectric layers **12***a* and **12***b* form one Seebeck element **10**. A plurality of the Seebeck elements **10** are connected in series between electrodes **24***a* and **24***b*.

The connection layers **14***a* and **14***b* are thermally connected to thermally conductive layers **16***a* (a first thermally conductive layer) and **16***b* (a second thermally conductive layer) in the −Z direction and the +Z direction (a second direction intersecting the surface), respectively. The thermally conductive layers **16***a* and **16***b* are thermally connected to base portions **22***a* and **22***b* through electrically insulating films **20***a* and **20***b*, respectively. The thermally conductive layers **16***a* and **16***b* penetrate through insulating layers **18***a* and **18***b*, respectively. The insulating layer **18***a* includes insulating layers **17***a* (a first insulating layer) and **17***b* (a second insulating layer). The insulating layer **17***b* is provided between the insulating layer **17***a* and the Seebeck element **10** and between the insulating layer **17***a* and the connection layers **14***a* and **14***b*. The insulating layer **18***b* includes insulating layers **17***c* (a third insulating layer) and **17***d* (a fourth insulating layer). The insulating layer **17***d* is provided between the insulating layer **17***c* and the Seebeck element **10** and between the insulating layer **17***c* and the connection layers **14***a* and **14***b*. The insulating layers **17***b* and **17***d* are in contact with each of the thermoelectric layers **12***a* and **12***b*, and are in contact with the thermally conductive layers **16***a* and **16***b*, respectively. The insulating layers **17***a* and **17***c* are in contact with the insulating layers **17***b* and **17***d*, respectively, are in contact with the insulating films **20***a* and **20***b*, respectively, and are in contact with the thermally conductive layers **16***a* and **16***b*, respectively. The thermal conductivities of the insulating layers **17***a* and **17***c* are smaller than the thermal conductivities of the connection layers **14***a* and **14***b* and the thermally conductive layers **16***a* and **16***b*, and the thermal conductivities of the insulating layers **17***b* and **17***d* are smaller than the thermal conductivities of the insulating layers **17***a* and **17***c*.

FIG. **3**A is a plan view of a thermoelectric conversion module in the first embodiment, and FIG. **3**B is a cross-sectional view taken along line A-A in FIG. **3**A. As illustrated in FIG. **3**A and FIG. **3**B, in a thermoelectric conversion module **100**, the base portions **22***a* and **22***b* face each other. A heat sink **33** is thermally connected to the upper surface of the base portion **22***b*. A surface of the base portion **22***a* facing the base portion **22***b* has a protruding portion. The base portion **22***a* has a section **35**, which protrudes toward the base portion **22***b*, and sections **36**, which do not protrude. The distance H between the base portions **22***a* and **22***b* in the section **36** is greater than the distance between the base portions **22***a* and **22***b* in the section **35**. For example, the base portion **22***b* has a flat plate shape, and the base portion **22***a* has a shape in which a protruding portion is provided on a flat plate. The protruding portion may be provided on the lower surface of the base portion **22***b*, or the protruding portions may be provided on both the upper surface of the base portion **22***a* and the lower surface of the base portion **22***b*. Although the planar shapes of the base portions **22***a*, **22***b* and the section **35** are illustrated as squares as an example, these planar shapes can be freely selected.

A support **34** is provided between the base portions **22***a* and **22***b* in the periphery of the base portions **22***a* and **22***b*. A thermal insulator **32** is provided between the base portions **22***a* and **22***b* surrounded by the support **34**. The thermal insulator **32** is, for example, a gas having a pressure lower than atmospheric pressure or a vacuum. The support **34** maintains the pressure or vacuum of the thermal insulator **32**. The support **34** mechanically supports the base portion **22***a* and the base portion **22***b*. The thermal conductivity of the thermal insulator **32** is smaller than the thermal conductivities of the thermoelectric conversion device **30**, the base portions **22***a* and **22***b*, and the support **34**.

The thermoelectric conversion device **30** includes a plurality of blocks **31***a* to **31***c*. In each of the blocks **31***a* to **31***c*, a plurality of the thermoelectric layers **12***a* and **12***b* are alternately arranged in the X direction. The blocks **31***a* to **31***c* are arranged in the Y direction. An electrode **24***c* connects the blocks **31***a* and **31***b*, and an electrode **24***d* connects the blocks **31***b* and **31***c*. Thus, the Seebeck elements **10** are connected in series between the electrodes **24***a* and **24***b*. Other configurations of the thermoelectric conversion device **30** are the same as those illustrated in FIG. **1** to FIG. **2**, and description thereof will be omitted.

In applications where the operating temperature is near room temperature or up to about several hundred degrees Celsius, the thermoelectric materials used for the thermoelectric layers **12***a* and **12***b* can be bismuth-telluride-based alloys, full-Heusler-based alloys, or half-Heusler-based alloys. Examples of the bismuth-tellurium-based alloy include $Bi_2Te_{3-x}Se_x$ as n-type and $Bi_{2-x}Sb_xTe_3$ as p-type. Examples of the full-Heusler-based alloy include $Fe_2VAl_{1-x}Ge_x$, $Fe_2VAl_{1-x}Si_x$, or $Fe_2VTa_xAl_{1-x}$ as n-type, $Fe_2V_{1-x}W_xAl$, $Fe_2V_{1-x}Ti_xAl$, or $Fe_2V_{1-x}Ti_xGa$ as p-type, and other materials containing Fe_2NbGa, Fe_2HfSi, Fe_2TaIn, Fe_2TiSn, or Fe_2ZrGe as a base material. Examples of the half-Heusler-based alloy include TiPtSn, $(Hf_{1-x}Zr_x)NiSn$, and NbCoSn as n-type, and $TiCoSn_xSb_{1-x}$, $Zr(Ni_{1-x}Co_x)Sn$, $Zr(Ni_{1-x}In_x)Sn$, and HfPtSn as p-type. When the n-type thermoelectric material and the p-type thermoelectric material are materials of the same base, the thermoelectric layers **12***a* and **12***b* can be easily formed. When the temperature range to be used is sufficiently higher than room temperature, Si, SiGe alloys, or GeSn alloys can also be used as thermoelectric materials for the thermoelectric layers **12***a* and **12***b*.

The thermoelectric layers **12***a* and **12***b* are made of, for example, the n-type and p-type materials exemplified above, respectively. The thermoelectric layers **12***a* and **12***b* may be made of materials with different bases among the materials exemplified above. In addition, one of the thermoelectric layers **12***a* and **12***b* may be made of the n-type or p-type material exemplified above, and the other of the thermoelectric layers **12***a* and **12***b* may be replaced with an appropriate metal that is not a thermoelectric material.

The connection layers **14***a* and **14***b* are preferably made of a material having a high electric conductivity and a high thermal conductivity. For example, metal layers of Cu, Al, Au, or Ag can be used. The connection layers **14***a* and **14***b* may be made of different materials.

As the insulating layers **17***a* and **17***c*, for example, inorganic insulators such as silicon oxide, alkyl group-containing silica or similar oxides and insulators (e.g., hydrogen silsesquioxane), resins (e.g., acrylic resins, epoxy resins, vinyl chloride resins, silicone resins, fluorine resins, phenol resins, bakelite resins, polyethylene resins, polycarbonate resins, polystyrene resins, polypropylene resins), or rubbers (e.g., natural rubber, ethylene-propylene rubber, chloroprene rubber, silicone rubber, butyl rubber, or polyurethane rubber) can be used. As the insulating layers **17***b* and **17***d*, porous substances using the above insulators (e.g., porous silicon or porous silica) can be used. Porous silicon is, for example, porous silicon using high-resistance silicon. Porous silica is, for example, porous silicon that has been made into an electrical and thermal insulator by oxidation or other means. The insulating layers **18***a* and **18***b* can be formed by chemical vapor deposition (CVD), sputtering, or spin coating.

The base portions **22***a* and **22***b* are preferably made of a material having a high thermal conductivity, and for example, a metal such as Cu, Al, Au or Ag, or ceramics such as Si or alumina can be used. The electrically insulating films **20***a* and **20***b* are preferably made of a material having high electrical insulating properties and high thermal conductivity, such as an aluminum oxide film. The insulating films **20***a* and **20***b* may be formed on the base portions **22***a* and **22***b* by sputtering or CVD. In the case that the base portions **22***a* and **22***b* are electrical insulators, the insulating films **20***a* and **20***b* may not be necessarily used. At least one of the base portions **22***a* and **22***b* can be formed by sputtering or CVD. This allows the base portions **22***a* and **22***b* to be thinned. At least one of the base portions **22***a* and **22***b* can be formed by plating. This allows the base portions **22***a* and **22***b* to be thick to some extent. In the case that at least one of the base portion **22***a* and **22***b* is formed of an oxide film or ceramics, a coating film formed by spin coating or the like can be used. As the base portions **22***a* and **22***b*, a structure (for example, a fin structure or a heat sink structure) and a material (for example, a heat dissipation sheet, a heat dissipation material or heat absorption material containing a volatile material, or Al with an anodized surface) having high heat exchange characteristics and high heat dissipation characteristics can be used.

The support **34** preferably has a low thermal conductivity, and is preferably made of a material harder than the thermal insulator **32** to support the base portions **22***a* and **22***b* and/or maintain a gas layer or vacuum. As the support **34**, for example, a polymer organic material such as resin or rubber can be used. For example, in the case that the thermal insulator **32** is solid, the yield strength of the support **34** is preferably higher than that of the thermal insulator **32** to reinforce the thermal insulator **32**.

Comparative Example 1

First, simulation was performed on a comparative example 1 in which the insulating layers **17***b* and **17***d* were not provided and the entire insulating layers **18***a* and **18***b* were used as the insulating layers **17***a* and **17***c*.

Simulation for Comparative Example 1

The structural parameters illustrated in FIG. **1**A to FIG. **3** were defined as follows.

- D: Widths of the base portions **22***a* and **22***b* in the X direction and the Y direction
- D': Widths of the section **35** in the X direction and the Y direction
- D_0: Length of the thermoelectric conversion device **30** (total length of the blocks **31***a* to **31***c*) in the X-direction
- H: Distance between the base portions **22***a* and **22***b* in the section **36**
- x: Widths of the support **34** in the X direction and the Y direction
- d: Pitch of the thermoelectric layers **12***a* and **12***b* in the X direction
- γ: Trade-off parameter, which is the parameter with which the width occupied by the thermoelectric layers **12***a* and **12***b* is γd
- γd: Widths of the thermoelectric layers **12***a* and **12***b* in the X direction
- (1−γ)d: Distance between the thermoelectric layers **12***a* and **12***b* in the X direction
- L: Lengths of the thermoelectric layers **12***a* and **12***b* in the Y direction
- t_s: Thicknesses of the thermoelectric layers **12***a* and **12***b* in the Z direction
- t_{ins1}: Thicknesses of the insulating layers **17***b* and **17***d* in the Z direction, $_{tins1}$ is 0 in the comparative example 1
- t_{ins2}: Thicknesses of the insulating layers **17***a* and **17***c* in the Z direction
- $t_C=t_{C1}+t_{C2}$: Thicknesses of the insulating layers **18***a* and **18***b* in the Z direction
- t_{C1}: Larger one of the distance between the end of the thermally conductive layer **16***a* and the center of the thermally conductive layer **16***b* in the X direction and the distance between the end of the thermally conductive layer **16***b* and the center of the thermally conductive layer **16***a* in the X direction
- t_{PI}: Thicknesses of the insulating films **20***a* and **20***b* in the Z direction
- m_0: Number of pairs of the thermoelectric layers **12***a* and **12***b* (i.e., the number of the Seebeck elements **10**)
- ΔT_s: Temperature difference between the lower surface of the base portion **22***a* and the upper surface of the base portion **22***b*
- P_{out}: Output power of the thermoelectric conversion device

The simulation conditions for each dimension and material were as follows.

$D \times D = 10$ mm×10 mm
$D' \times D' = 3$ mm×3 mm
$D_0 = 9$ mm
H=5 mm
x=0.5 mm
$t_S = 1000$ nm
$t_{PI} = 100$ nm

Thermoelectric Layers **12***a* and **12***b*

Material: BiTe
Seebeck coefficient=$S_p - S_n$: 434 μV/K
Thermal conductivity $\lambda=(\lambda_p+\lambda_n)/2$:1.43 W/(m·K)
Electrical resistivity $\rho=(\rho_p+\rho n)/2$: 8.11 μΩ·m

Note that λ_n and ρ_n are the thermal conductivity and electrical resistivity of the thermoelectric layer **12***a*, respectively, and λ_p and ρ_p are the thermal conductivity and electrical resistivity of the thermoelectric layer **12***b*, respectively.

Connection Layers **14***a*, **14***b*, Thermally Conductive Layers **16***a*, **16***b*

Material: Cu
Thermal conductivity 2_C: 386 W/(m·K)
Electric resistivity pc: 17 nΩ·m

Insulating Films **20***a* and **20***b*

Material: AlO_x
Thermal conductivity λ_{PI}: 1.5 W/(m·K)

Support **34**
Material: Organic material
Thermal conductivity 2_{WL}: 0.15 W/(m·K)
Thermal Insulator **32**
Vacuum
Contact Resistance
BiTe and Cu
Electrical contact-resistance r_{PC}: 1.0 $\Omega\cdot\mu m^2$
Thermal contact-resistance k_{PC}: 140 $\mu m^2\cdot K/mW$
Cu and AlO_x
Thermal contact-resistance kc-pi: 3.4 $\mu m^2\cdot K/mW$

The temperature difference between the body temperature of the human body and the temperature of the atmosphere was set as 10 K. The electrical contact-resistance is an electrical resistance per unit area on a surface where two materials are in contact with each other, and the thermal contact-resistance is a thermal resistance per unit area on a surface where two materials are in contact with each other.

The simulation was performed for the following three materials as the insulating layers **18***a* and **18***b*.

Sample PS
Material: Porous silica
Thermal conductivity λ_{PS}: 35.7 mW/(m·K)
Sample HSQ
Material: Hydrogen silsesquioxane
Thermal conductivity λ_{HSQ}: 0.3 W/(m·K)
Sample SiO_2
Material: SiO_2
Thermal conductivity λ_{SiO2}: 0.9 W/(m·K)

PS has a low thermal conductivity but is brittle. Therefore, it is difficult to form a thick layer. SiO_2 has high mechanical strength and can be easily formed thick, but has high thermal conductivity. HSQ (hydrogen silsesquioxane) is a molecule formed by doping silsesquioxane, which is an intermediate material between silica and silicon, with hydrogen, and has a less mechanical strength than SiO_2 but has a lower thermal conductivity than SiO_2.

Table 1 is not related to $t_{C2}+t_{C1}$ presented in FIG. **2**, and is a table presenting optimized output power P_{out} and each parameter in the case where each of the insulating layers **18***a* and **18***b* has a single-layer structure and t_{C2}=30 μm.

TABLE 1

Sample	PS	HSQ	SiO_2
P_{out} [μW]	16.15	7.055	3.014
γd [μm]	7.92	3.21	2.06
(1 − γ)d [μm]	2.93	2.06	2.15
m_0 [pairs]	415	854	1069
L [μm]	7.18	1.25	0.525
t_{C1} [μm]	9.38	4.24	3.14

As presented in Table 1, although the output power P_{out} of the sample PS is 16.15 μW, the output power P_{out} of the sample HSQ is equal to or less than ½ of that of the sample PS, and the output power P_{out} of the sample SiO_2 is equal to or less than ⅕ of that of the sample PS. Since the thermal conductivities of the insulating layers **18***a* and **18***b* vary from sample to sample, the parameters for optimizing the output power P_{out} vary from sample to sample.

In the comparative example 1, when PS is used as the insulating layers **18***a* and **18***b*, although the output power P_{out} is large, the mechanical strength is weak, and the process is difficult. When HSQ and SiO_2 are used as the insulating layers **18***a* and **18***b*, the mechanical strength is sufficient and the process is easy, but the output power P_{out} is greatly reduced.

The leakage of heat flow from the thermoelectric layers **12***a* and **12***b* and the thermally conductive layers **16***a* and **16***b* to the insulating layers **18***a* and **18***b* in the samples PS and HSQ of the comparative example 1 was simulated using a highly accurate distributed constant circuit model.

FIG. **4** illustrates heat flow in the comparative example 1. The lower surface of the insulating film **20***a* was set to a high temperature, and the upper surface of the insulating film **20***b* was set to a low temperature. Heat flow **54** leaking from the thermally conductive layer **16***a* to the insulating layer **18***a* and heat flow **53** flowing from the insulating layer **18***a* into each of the thermoelectric layers **12***a* and **12***b* were simulated. The positions X of the X coordinate of the thermoelectric layers **12***a* and **12***b* were normalized. The position X at which the thermoelectric layers **12***a* and **12***b* were in contact with the connection layer **14***b* was defined as 0, and the position X at which the thermoelectric layers **12***a* and **12***b* were in contact with the connection layer **14***a* was defined as 1. The position Z of the Z coordinate of the thermally conductive layer **16***a* was normalized. The position Z at which the thermally conductive layer **16***a* and the insulating film **20***a* were in contact with each other was defined as 0, and the position Z at which the thermally conductive layer **16***a* and the connection layer **14***a* were in contact with each other was defined as 1.

FIG. **5**A and FIG. **5**B are graphs presenting normalized heat flow versus normalized X and normalized Z, respectively. In the simulation, the range of 0 to 1 of the normalized X and the range of 0 to 1 of the normalized Z were divided into 10 ranges and 15 ranges, respectively. Dots in FIG. **5**A and FIG. **5**B indicate the sum of the normalized heat flows in the respective divided ranges. A straight line is a line connecting dots. FIG. **5**A presents the normalized heat flow **53** flowing from the insulating layer **18***a* into the thermoelectric layers **12***a* and **12***b*. The normalized heat flow is heat flow obtained by normalizing each heat flow by the total heat flow flowing into the insulating film **20***a* from the outside. As presented in FIG. **5**A, for the sample HSQ, in a region **51**, the normalized heat flow **53** is large around the normalized x=0, and the normalized heat flow **53** decreases as the normalized x increases. This means that as the normalized X increases, the temperatures of the thermoelectric layers **12***a* and **12***b* increase. As the temperatures of the thermoelectric layers **12***a* and **12***b* decrease, the heat flow flowing in from the insulating layer **18***a* increases. In a region **50**, the normalized heat flow **53** increases as the normalized X increases.

FIG. **5**B presents the normalized heat flow **54** leaking from the thermally conductive layer **16***a* to the insulating layer **18***a*. As presented in FIG. **5**B, for the sample HSQ, the normalized heat flow **54** is substantially zero in a region **52**. In the region **50**, the normalized heat flow **54** increases as the normalized Z increases. As is clear from above, it has been revealed that in the region **50** of FIG. **4**, there is a heat flow from the thermally conductive layer **16***a* to the thermoelectric layers **12***a* and **12***b* through the insulating layer **18***a*. This may be considered because the heat flow that is less likely to flow from the connection layer **14***a* to the thermoelectric layers **12***a* and **12***b* because of the thermal contact-resistance k_{PC} between the thermally conductive layer **16***a* and the thermoelectric layers **12***a* and **12***b* passes through the region **50**. However, since the thermal contact-resistance k_{PC} is sufficiently small, it is considered that the heat flow through the region **50** is due to the high thermal conductivity of the insulating layer **18***a*. In the sample PS, the normalized heat flows **53** and **54** in FIG. **5**A and FIG. **5**B are smaller than those in the sample HSQ. This is considered because, in the sample PS, the thermal conductivity of the insulating layer **18***a* is small and thus heat passing through the insulating layer **18***a* is small.

FIG. **6** illustrates heat flow in the comparative example 1. The lower surface of the insulating film **20***a* was set to a high temperature, and the upper surface of the insulating film **20***b* was set to a low temperature. Heat flow **58** leaking from each of the thermoelectric layers **12***a* and **12***b* to the insulating layer **18***b* and heat flow **59** flowing from the insulating layer **18***b* to the thermally conductive layer **16***b* were simulated. The normalized X is the same as in FIG. **4**. The position Z at which the thermally conductive layer **16***b* and the connection layer **14***b* were in contact with each other was defined as 0, and the position Z at which the thermally conductive layer **16***b* and the insulating film **20***b* were in contact with each other was defined as 1.

FIG. **7**A and FIG. **7**B are graphs presenting normalized heat flow versus normalized X and normalized Z, respectively. FIG. **7**A presents the normalized heat flow **58** flowing from the thermoelectric layers **12***a* and **12***b* into the insulating layer **18***b*. As presented in FIG. **7**A, for the sample HSQ, in a region **56**, the normalized heat flow **58** is large around the normalized X=1, and the normalized heat flow **58** decreases as the normalized X decreases. This is due to the temperature distribution in the thermoelectric layers **12***a* and **12***b*. In a region **55**, the normalized heat flow **58** increases as the normalized X decreases.

FIG. **7**B presents the normalized heat flow **59** flowing from the insulating layer **18***b* into the thermally conductive layer **16***b*. As presented in FIG. **7**B, in the sample HSQ, the normalized heat flow **59** is substantially zero in a region **57**. In the region **55**, the normalized heat flow **59** increases as the normalized Z decreases. As described above, it has been revealed that in the region **55** of FIG. **6**, there is heat flow from the thermoelectric layers **12***a* and **12***b* to the thermally conductive layer **16***b* through the insulating layer **18***b*. It is considered that the heat flow through the region **55** is due to the high thermal conductivity of the insulating layer **18***b*. Also in FIG. **7**A and FIG. **7**B, the normalized heat flows **58** and **59** of the sample PS are smaller than those of the sample HSQ. This is considered because, in the sample PS, the thermal conductivity of the insulating layer **18***b* is small, and thus the heat flow passing through the insulating layer **18***b* is small.

As described above, the heat flow passing through the insulating layers **18***a* and **18***b* includes two heat flows: the heat flow depending on the temperature distribution of the thermoelectric layers **12***a* and **12***b*, and the heat flow that passes through the regions **50** and **55** because of the high thermal conductivities of the insulating layers **18***a* and **18***b*. The existence of such two heat flows having different mechanisms is not suggested in Patent Document 2. It is considered that the output power P_{out} is lower in the samples HSQ and SiO_2 than in the sample PS because of the leakage of the heat flow to the insulating layers **18***a* and **18***b* according to these two mechanisms. The output power of the first embodiment in the case where the two mechanisms described above are present was simulated.

Simulation for First Embodiment

The sample HSQ/PS is a sample adopting HSQ as the insulating layers **17***a* and **17***c* and adopting PS as the insulating layers **17***b* and **17***d*. The sample SiO_2/PS is a sample adopting SiO_2 as the insulating layers **17***a* and **17***c* and adopting PS as the insulating layers **17***b* and **17***d*. The output power P_{out} optimized by varying the thicknesses t_{ins1} of the insulating layers **17***b* and **17***d* was simulated for three conditions: t_{C1}=7 μm and t_{C2}=1 μm, t_{C1}=8 μm and t_{C2}=10 μm, and t_{C1}=9.4 μm and t_{C2}=30 μm.

FIG. **8**A to FIG. **8**C are graphs presenting P_{out} versus t_{ins1} in the first embodiment. The samples HSQ/PS and SiO_2/PS are presented as the first embodiment, and the sample PS is presented as the comparative example 1. In the sample PS, $t_{ins1}=t_{C1}+t_{C2}$, but for comparison with the samples HSQ/PS and SiO_2/PS, P_{out} is illustrated by a dotted straight line that takes a constant value regardless of the value of t_{ins1}. As presented in FIG. **8**A to FIG. **8**C, the output power P_{out} of both samples HSQ/PS and SiO_2/PS is less than or equal to ½ of that of the sample PS around t_{ins1}=0. As t_{ins1} increases, the output power P_{out} approaches that of the sample PS, and at $t_{ins1}=t_{C1}$, the output power P_{out} of the samples HSQ/PS and SiO_2/PS is almost the same as the output power P_{out} of the sample PS.

Table 2 is a table presenting the ratio P_{out}HSQ/P_{out}PS indicating the output voltage P_{out}HSQ of the sample HSQ/PS with respect to the output voltage P_{out}PS of the sample PS.

TABLE 2

P_{out}HSQ/P_{out}PS	$t_{ins1} = t_{C1}$	$t_{ins1} = t_{C1}/2$
t_{C2} = 1 μm	0.996	0.935
t_{C2} = 10 μm	0.988	0.920
t_{C2} = 30 μm	0.984	0.909

Table 3 is a table presenting the ratio $P_{out}SiO_2/P_{out}$PS indicating the output voltage $P_{out}SiO_2$ of the sample SiO_2/PS with respect to the output voltage P_{out}PS of the sample PS.

TABLE 3

$P_{out}SiO_2/P_{out}$PS	$t_{ins1} = t_{C1}$	$t_{ins1} = t_{C1}/2$
t_{C2} = 1 μm	0.999	0.927
t_{C2} = 10 μm	0.988	0.906
t_{C2} = 30 μm	0.983	0.893

Table 2 and Table 3 present P_{out}HSQ/P_{out}PS and $P_{out}SiO_2/P_{out}$PS when t_{C2} is 1 μm, 10 μm, or 30 μm, and t_{ins1} is t_{C1} or $_{tC}/2$. As presented in Table 2 and Table 3, when $t_{ins1}=t_{C1}$, P_{out}HSQ and $P_{out}SiO_2$ are substantially the same as P_{out}PS regardless of t_{C2}. When $t_{ins1}=t_{C1}/2$, P_{out}HSQ and $P_{out}SiO_2$ are approximately 90% of P_{out}PS regardless of t_{C2}. As presented in FIG. **8**A to FIG. **8**C, when $t_{ins1}=t_{C1}/4$, P_{out}HSQ and $P_{out}SiO_2$ are approximately 75% of P_{out}PS, and when $t_{ins1}=t_{C1}/3$, P_{out}HSQ and $P_{out}SiO_2$ are approximately 85% of P_{out}PS. As described above, the output power P_{out} cannot be increased unless the thicknesses t_{ins1} of the insulating layers **17***b* and **17***d* are increased to a predetermined value or greater.

The reasons why the output power P_{out} cannot be increased unless the thicknesses t_{ins1} of the insulating layers **17***d* and **17***b* are increased are considered as follows. First, in FIG. **4**, the heat flow **53** flowing from the insulating layer **18***a* into the thermoelectric layers **12***a* and **12***b* around the normalized X=0 passes through the section from the thermoelectric layers **12***a* and **12***b* to about t_{C1} in the insulating layer **18***a*. Further, the region **50** in which the heat flow **54** leaking from the thermally conductive layer **16***a* to the insulating layer **18***a* is present extends to the section from the thermoelectric layers **12***a* and **12***b* to about t_{C1}. Also in FIG. **6**, the heat flow **58** leaking from the thermoelectric layers **12***a* and **12***b* to the insulating layer **18***b* around the normalized X=1 passes through the section from the thermoelectric layers **12***a* and **12***b* to about t_{C1} in the insulating layer **18***b*. Further, the region **55** in which the heat flow **59** flowing from the insulating layer **18***b* into the thermally conductive layer **16***b* is present extends to the section from the thermoelectric layers **12***a* and **12***b* to about t_{C1}.

Such a behavior of the output power P_{out} with respect to the thicknesses t_{ins1} of the insulating layers **17***b* and **17***d* is not suggested by the description of Patent Document 2, and is a finding obtained by starting simulation of the highly accurate distributed constant circuit model as presented in FIG. **4** to FIG. **7**B.

In the first embodiment, the thicknesses t_{ins1} of the insulating layers **17***d* and **17***b* are adjusted to be $t_{C1}/4$ or greater. This allows the output power P_{out} to be equal to or greater than 75% of the output power P_{out} of the sample PS. Note that t_{C1} is the larger one of the distance between the end of the thermally conductive layer **16***a* at the thermoelectric layer **12***a* side and the center of the thermally conductive layer **16***b* in the X direction and the distance between the end of the thermally conductive layer **16***a* at the thermoelectric layer **12***b* side and the center of the thermally conductive layer **16***b* in the X direction. The thickness t_{ins1} is more preferably $t_{C1}/3$ or greater, further preferably $t_{C1}/2$ or greater. This is because the simulation of the highly accurate distributed constant circuit model has revealed that the output power of about 90% of the output power of the sample PS is obtained by adjusting the thicknesses t_{int1} of the insulating layers **17***b* and **17***d* to be ½ of t_{C1}, and the output power of about 85% of the output power of the sample PS is obtained by adjusting the thickness t_{int1} to be ⅓ of t_{C1}.

Even if the thickness t_{ins1} becomes thicker than t_{C1}, the output power P_{out} does not increase. Therefore, in order to increase the mechanical strength of the insulating layers **18***a* and **18***b*, the thickness tins is preferably $2 \times t_{C1}$ or less, more preferably $1.5 \times t_{C1}$ or less, and still more preferably t_{C1} or less. The preferable range of the thickness t_{ins1} (for example, $t_{C1}/2$ or greater and t_{C1} or less) does not change even when the materials of the insulating layers **17***b* and **17***d* and T_{C2} are changed as presented in FIG. **8**A to FIG. **8**C. Further, the thickness tins of either one of the insulating layers **17***b* and **17***d* may be $t_{C1}/4$ or greater and $2 \times t_{C1}$ or less.

In order to increase the mechanical strength of the insulating layers **18***a* and **18***b*, the thicknesses t_{ins2} of the insulating layers **17***a* and **17***b* are preferably large. Therefore, t_{ins2} is preferably $t_{ins1}/2$ or greater, more preferably t_{ins1} or greater, and further preferably $1.5 \times t_{ins1}$ or greater.

The thermal conductivities of the insulating layers **18***a* and **18***b* are only required to be lower than those of the thermally conductive layers **16***a* and **16***b*. The thermal conductivities of the insulating layers **17***a* and **17***c* are preferably equal to or less than 1/300 of, more preferably equal to or less than 1/1000 of the thermal conductivities of the thermally conductive layers **16***a* and **16***b*. The thermal conductivities of the insulating layers **17***b* and **17***d* are only required to be lower than the thermal conductivities of the insulating layers **17***a* and **17***c*, and are preferably equal to or less than ⅕ of, more preferably equal to or less than 1/10 of, further preferably equal to or less than 1/50 of the thermal conductivities of the insulating layers **17***a* and **17***c*. In order to make the thermal conductivities of the insulating layers **17***b* and **17***d* lower than those of the insulating layers **17***a* and **17***c*, the insulating layers **17***b* and **17***d* may be porous and the insulating layers **17***a* and **17***c* may be non-porous. When the insulating layers **17***b* and **17***d* are porous, the porosity (porous ratio) of the insulating layers **17***b* and **17***d* is preferably 10% or greater, and more preferably 50% or greater. This configuration allows the thermal conductivities of the insulating layers **17***b* and **17***d* to be low. When the insulating layers **17***a* and **17***c* are non-porous, the porosity of the insulating layers **17***a* and **17***b* is preferably 1% or less and more preferably 0.1% or greater. This configuration can increase the mechanical strength of the insulating layers **17***a* and **17***b*.

Table 4 is a table presenting the percentage of increase of the output power P_{out} of the sample HSQ/PS with respect to that of the sample HSQ and the percentage of increase the output power P_{out} of the sample SiO_2/PS with respect to that of the sample SiO_2. Note that t_{C2}=30 μm and $t_{ins1}=t_{C1}$.

TABLE 4

T_{C2} = 30 μm, T_{ins1} = T_{C1}.	
Percentage of increase of P_{out} of HSQ/PS with respect to HSQ	125%
Percentage of increase of P_{out} of SiO_2/PS with respect to SiO_2	426%

As presented in Table 4, the sample HSQ/PS has P_{out} increased by 125% compared to the sample HSQ, and the sample SiO_2/PS has P_{out} increased by 426% compared to the sample SiO_2.

FIG. **9**A to FIG. **9**E are graphs presenting the current I and the output power P_{out} versus the output voltage V_{out} in each sample. FIG. **9**A presents the sample PS, FIG. **9**B presents the sample HSQ, FIG. **9**C presents the sample SiO_2, FIG. **9**D presents the sample HSQ/PS, and FIG. **9**E presents the sample SiO_2/PS. A plurality of modules in which the areas of the base portions **22***a* and **22***b* are D×D=1 cm^2 are connected in series and/or in parallel, and a mounting area S_A is varied from 20 cm^2 to 120 cm^2 in steps of 20 cm^2. Note that t_{C2}=30 μm for all samples and $t_{ins1}=t_{C1}$ for the samples HSQ/PS and SiO_2/PS.

As presented in FIG. **9**A to FIG. **9**E, when the output voltage V_{out} is substantially 1 V, the power P_{out} peaks. As presented in FIG. **9**A, in the sample PS, when the mounting area S_A is 120 cm^2, an output power P_{out} of about 2 mW is achieved. However, in the sample PS, the mechanical strength of the insulating layers **18***a* and **18***b* is low. As presented in FIG. **9**B and FIG. **9**C, in the samples HSQ and SiO_2, although the mechanical strength of the insulating layers **18***a* and **18***b* is high, the output power P_{out} is 1 mW or equal to or less than 0.5 mW even when the mounting area S_A is set to 120 cm^2. As presented in FIG. **9**D and FIG. **9**E, in the samples HSQ/PS and SiO_2/PS, when S_A is 120 cm^2, the output power P_{out} is about 2 mW, which is almost the same as that of the sample PS. Since the insulating layers **17***a* and **17***c* are made of HSQ or SiO_2, mechanical strength can be ensured.

First Variation of First Embodiment

FIG. **10** is an enlarged cross-sectional view of a thermoelectric conversion device in a first variation of the first embodiment. As illustrated in FIG. **10**, in the first variation of the first embodiment, the thermoelectric layers **12***a* and **12***b* have different lengths in the X direction. The distance between the end of the thermally conductive layer **16***b* at the thermoelectric layer **12***b* side and the center of the thermally conductive layer **16***a* in the X direction is represented by d_1, and the distance between the end of the thermally conductive layer **16***b* at the thermoelectric layer **12***a* side and the center of the thermally conductive layer **16***b* in the X direction is represented by dz. The pitch in the X direction is represented by d.

In the case that the distances d_1 and d_2 are different from each other as in the first variation of the first embodiment, it is required to reduce both the heat flow bypassing the insulating layer **18***a* and the heat flow bypassing the insulating layer **18***b*. Therefore, the larger distance d_2 of the distances d_1 and d_2 is used as the reference. That is, tins' is preferably $d_2/4$ or greater, more preferably $d_2/3$ or greater, and further preferably $d_2/2$ or greater. Further, t_{ins1} is preferably $2 \times d_2$ or less, more preferably $1.5 \times d_2$ or less, and further preferably d_2 or less. As in the first embodiment, the distances d_1 and d_2 may be the same to the extent of the manufacturing error, or as in the first variation of the first embodiment, the distances d_1 and d_2 may be different to the extent of the manufacturing error or greater. In the above described embodiment, the insulating layers **18***a* and **18***b* whose cross sections are illustrated in FIG. **10** are repeatedly arranged at the pitch d in the X direction. Since the pitch d is a constant value, there are two distances d_1 and dz. Note that the pitch d may not be necessarily constant. In this case, the largest distance of a plurality of the distances d**1** and a plurality of the distances d**2** can be used as the reference.

In the above-described embodiment, the second insulating layer that is penetrated by the first thermally conductive layer, has a smaller thermal conductivity than the first insulating layer, is provided between the first insulating layer and the first thermoelectric layer and the second thermoelectric layer, and has a thickness equal to or greater than ¼ of the larger distance of the distance between the end of the first thermally conductive layer at a side of the first thermoelectric layer and the center of the second connection layer in the first direction and the distance between the end of the first thermally conductive layer at a side of the second thermoelectric layer and the center of the second connection layer in the first direction is used as the insulating layers **17***b* and **17***d* to which a porous substance of the insulators illustrated in FIG. **2** or FIG. **10** is adopted.

As illustrated in FIG. **1**A to FIG. **2**, in the case that the insulating layer **17***b* is in contact with the thermoelectric layers **12***a* and **12***b* and the insulating layer **17***a*, and the insulating layer **17***d* is in contact with the thermoelectric layers **12***a* and **12***b* and the insulating layer **17***a*, the space **15** (i.e., an air gap) as illustrated in FIG. 8 of Patent Document 2 is not formed between the base portion **22***a* and the thermoelectric layers **12***a* and **12***b* or between the base portion **22***b* and the thermoelectric layers **12***a* and **12***b*. This is because the base portion **22***a*, the thermoelectric layers **12***a* and **12***b*, and the base portion **22***b* are produced by a micro-stacking process such as a semiconductor-forming process. As a result, a thermoelectric conversion device having a very high density and a small size can be provided at a low manufacturing cost, and the strength of the thermoelectric conversion device can be increased.

When the thermal conductivities of the insulating layers **17***b* and **17***d* are adjusted to be smaller than the thermal conductivities of the insulating layers **17***a* and **17***c* in the thermoelectric conversion device in which no air gap is formed, the simulation results of FIG. **8**A to FIG. **8**C can be applied. That is, by adjusting each of the thicknesses of the insulating layers **17***b* and **17***d* having low thermal conductivity to be equal to or greater than ¼ of t_{C1}, the output power P_{out} can be increased as compared with the case where all of the insulating layers **18***a* and **18***b* are made of a material having a low thermal conductivity. When the insulating layers **17***b* and **17***d* are made of porous silica and the insulating layers **17***a* and **17***c* are made of HSQ or SiO_2 as presented in FIG. **8**A to FIG. **8**C, the output power can be increased to, for example, 75% or greater as compared with the case where all of the insulating layers **18***a* and **18***b* are made of HSQ or SiO_2.

Further, as presented in FIG. **8**A to FIG. **8**C, even if each of the thicknesses of the insulating layers **17***b* and **17***d* is adjusted to be larger than twice t_{C1}, the output power is not improved. Therefore, by providing the insulating layers **17***a* and **17***c* having high thermal conductivity and high mechanical strength and adjusting the thicknesses of the insulating layers **17***b* and **17***d* having low mechanical strength to be equal to or less than twice t_{C1}, the mechanical strength of the thermoelectric conversion device can be increased as compared with the case where all of the insulating layers **18***a* and **18***b* are made of a material having a low mechanical strength such as porous silica. As described above, it is possible to reduce a decrease in the output power P_{out} while ensuring the mechanical strength of the thermoelectric conversion device.

In the simulations in FIG. **8**A to FIG. **8**C, for the samples HSQ/PS and SiO_2/PS, the thermal conductivities of the insulating layers **17***b* and **17***d* (porous silica) are 1/8.4 times and 1/25.2 times the thermal conductivities of the insulating layers **17***a* and **17***c* (HSQ and SiO_2), respectively. Further, the thermal conductivities of the insulating layers **17***b* and **17***d* (porous silica) are 1/10800 times the thermal conductivities of the connection layers **14***a* and **14***b* and the thermally conductive layers **16***a* and **16***b* (Cu).

In order to obtain the same effect as the simulation results in FIG. **8**A to FIG. **8**C, the respective ranges of the thermal conductivities of the insulating layers **17***b* and **17***d* are preferably equal to or less than 1/5 times and equal to or greater than 1/100 times the thermal conductivities of the insulating layers **17***a* and **17***c*. By adjusting the thermal conductivities of the insulating layers **17***b* and **17***d* to be equal to or less than 1/5 times the thermal conductivities of the insulating layers **17***a* and **17***c*, the heat flow through the insulating layers **17***b* and **17***d* can be reduced to substantially the same range as that of the simulation result. As a result, a decrease in output power can be reduced. Furthermore, by adjusting the thermal conductivities of the insulating layers **17***b* and **17***d* to be equal to or greater than 1/100 times the thermal conductivities of the insulating layers **17***a* and **17***c*, a material having high mechanical strength can be used for the insulating layers **17***a* and **17***c*. This allows the mechanical strength of the thermoelectric conversion device to be ensured while the heat flow through the insulating layers **17***b* and **17***d* is reduced to substantially the same range as that of the simulation results described above.

The respective ranges of the thermal conductivities of the insulating layers **17***b* and **17***d* are preferably equal to or less than 1/300 times and equal to or greater than 1/30000 times the thermal conductivities of the connection layers **14***a* and **14***b* and the thermally conductive layers **16***a* and **16***b*. By adjusting the thermal conductivities of the insulating layers **17***b* and **17***d* to be equal to or less than 1/300 times the thermal conductivities of the connection layers **14***a* and **14***b* and the thermally conductive layers **16***a* and **16***b*, the thermal conductivities of the connection layers **14***a* and **14***b* and the thermally conductive layers **16***a* and **16***b* can be made high, and the heat flow through the insulating layers **17***b* and **17***d* can be reduced. Therefore, a decrease in the output power can be reduced. By adjusting the thermal conductivities of the insulating layers **17***b* and **17***d* to be equal to or greater than 1/30000 times the thermal conductivities of the connection layers **14***a* and **14***b* and the thermally conductive layers **16***a* and **16***b*, a practical material such as porous silica that can be applied to a micro-stacking process such as a semiconductor-forming process can be used as the insulating layers **17***b* and **17***d*. Therefore, the cost can be reduced. Further, in the case that the thermal conductivities of the insulating layers **17***b* and **17***d* are within the above range, each of the thicknesses of the insulating layers **17***b* and **17***d* is preferably adjusted to be equal to or greater than ¼ times and equal to or less than 2 times t_{C1}.

To obtain the same effect as the simulation results of FIG. **8**A to FIG. **8**C, the thermal conductivities of the insulating layers **17***b* and **17***d* are more preferably equal to or less than 1/10 times, further preferably equal to or less than 1/20 times the thermal conductivities of the insulating layers **17***a* and **17***c*. The thermal conductivities of the insulating layers **17***b* and **17***d* are more preferably equal to or less than 1/1000 times, further preferably equal to or less than 1/5000 times the thermal conductivities of the connection layers **14***a* and **14***b* and the thermally conductive layers **16***a* and **16***b*.

In the case that the thermal conductivities of the thermoelectric layers **12***a* and **12***b* are low, temperature distribution occurs in the thermoelectric layers **12***a* and **12***b* in the comparative example 1. Therefore, the heat flow flowing from the insulating layer **18***a* into the thermoelectric layers **12***a* and **12***b*, such as the heat flow **53** in FIG. **4**, and the heat flow flowing out from the thermoelectric layers **12***a* and **12***b* to the insulating layer **18***b*, such as the heat flow **58** in FIG. **6**, increase. In the simulations of FIG. **8**A to FIG. **8**C, the thermal conductivities of the thermoelectric layers **12***a* and **12***b* (BiTe) are 1/270 times the thermal conductivities of the connection layers **14***a* and **14***b* and the thermally conductive layers **16***a* and **16***b* (Cu). Therefore, in order to apply the simulation results of FIG. **8**A to FIG. **8**C, the thermal conductivities of the thermoelectric layers **12***a* and **12***b* are preferably equal to or less than 1/50 times the thermal conductivities of the connection layers **14***a* and **14***b* and the thermally conductive layers **16***a* and **16***b*.

In order to obtain the same effect as the simulation results of FIG. **8**A to FIG. **8**C, the thermal conductivities of the thermoelectric layers **12***a* and **12***b* are more preferably equal to or less than 1/100 times the thermal conductivities of the connection layers **14***a* and **14***b* and the thermally conductive layers **16***a* and **16***b*. The thermal conductivities of the thermoelectric layers **12***a* and **12***b* are, for example, equal to or greater than 1/1000 times the thermal conductivities of the connection layers **14***a* and **14***b* and the thermally conductive layers **16***a* and **16***b*.

If the thermal conductivities of the thermoelectric layers **12***a* and **12***b* are too low, the heat flow flowing in the thermoelectric layers **12***a* and **12***b* decreases. In the simulations of FIG. **8**A to FIG. **8**C, the thermal conductivities of the thermoelectric layers **12***a* and **12***b* (BiTe) are 40 times the thermal conductivities of the insulating layers **17***b* and **17***d* (porous silica). Therefore, in order to obtain the same effect as the simulation of FIG. **8**A to FIG. **8**C, the thermal conductivities of the thermoelectric layers **12***a* and **12***b* are preferably larger than the thermal conductivities of the insulating layers **17***b* and **17***d*. In order to apply the simulation results of FIG. **8**A to FIG. **8**C, the thermal conductivities of the thermoelectric layers **12***a* and **12***b* are more preferably equal to or greater than 10 times the thermal conductivities of the insulating layers **17***b* and **17***d*. The thermal conductivities of the thermoelectric layers **12***a* and **12***b* are, for example, equal to or less than 100 times the thermal conductivities of the insulating layers **17***b* and **17***d*.

Although preferred embodiments of the present invention have been described so far, the present invention is not limited to those particular embodiments, and various changes and modifications may be made to them within the scope of the invention claimed herein.

DESCRIPTION OF REFERENCE NUMERALS

10 Seebeck element
12*a*, **12***b* thermoelectric layer
14*a*, **14***b* connection layer
16*a*, **16***b* thermally conductive layer
17*a* to **17***d*, **18***a*, **18***b* insulating layer
22*a*, **22***b* base portion
24*a* to **24***d* electrode

The invention claimed is:

1. A thermoelectric conversion device comprising:

first thermoelectric layers and second thermoelectric layers that are alternately provided in a first direction parallel to surfaces of the first thermoelectric layers and the second thermoelectric layers, the first thermoelectric layers having conductivity types opposite to those of the second thermoelectric layers;

first connection layers and second connection layers, each of the first connection layers and the second connection layers being electrically and thermally connected to one of the first thermoelectric layers and one of the second thermoelectric layers between the one of the first thermoelectric layers and the one of the second thermoelectric layers, the first connection layers and the second connection layers being alternately provided in the first direction;

first thermally conductive layers that are thermally connected to the first connection layers, respectively, the first thermally conductive layers extending in a second direction intersecting the surfaces;

a first insulating layer through which the first thermally conductive layers penetrate, the first insulating layer having a thermal conductivity smaller than thermal conductivities of the first thermally conductive layers;

a second insulating layer through which the first thermally conductive layers penetrate, the second insulating layer having a thermal conductivity smaller than the thermal conductivity of the first insulating layer, the second insulating layer being provided between the first insulating layer and the first thermoelectric layers and between the first insulating layer and the second thermoelectric layers, the second insulating layer having a thickness equal to or greater than ¼ of a larger distance of a first distance between an end of one of the first thermally conductive layers and a center of one of the second connection layers in the first direction and a second distance between an end of another one of the first thermally conductive layers and the center of the one of the second connection layers in the first direction, the end of the one of the first thermally conductive layers being at a side of the one of the first thermoelectric layers, the one of the first thermoelectric layers being closest to the one of the first thermally conductive layers among the first thermoelectric layers, the one of the second connection layers being closest to the one of the first thermoelectric layers among the second connection layers, said another one of the first thermally conductive layers being adjacent to the one of the first thermally conductive layers and being closest to the one of the second connection layers among the first thermally conductive layers, the end of said another one of the first thermally conductive layers being at a side of the one of the second thermoelectric layers, the one of the second thermoelectric layers being closest to the one of the second connection layers among the second thermoelectric layers.

2. The thermoelectric conversion device according to claim **1**, further comprising:

second thermally conductive layers that are thermally connected to the second connection layers, respectively, the second thermally conductive layers being provided at a side opposite to the first thermally conductive layers with respect to the first thermoelectric layers and the second thermoelectric layers, the second thermally conductive layers extending in the second direction;

a third insulating layer through which the second thermally conductive layers penetrate, the third insulating layer having a thermal conductivity smaller than thermal conductivities of the second thermally conductive layers; and

a fourth insulating layer through which the second thermally conductive layers penetrate, the fourth insulating layer having a thermal conductivity smaller than the thermal conductivity of the third insulating layer, the fourth insulating layer being provided between the third insulating layer and the first thermoelectric layers and between the third insulating layer and the second thermoelectric layers, the fourth insulating layer having a thickness equal to or greater than ¼ of the larger distance.

3. The thermoelectric conversion device according to claim **1**, wherein the thickness of the second insulating layer is equal to or less than twice the larger distance.

4. The thermoelectric conversion device according to claim **1**, wherein a thickness of the first insulating layer is equal to or greater than ½ of the thickness of the second insulating layer.

5. The thermoelectric conversion device according to claim **1**, wherein the second insulating layer is porous, and the first insulating layer is non-porous.

6. The thermoelectric conversion device according to claim **1**, wherein the second insulating layer is in contact with the first thermoelectric layers and the second thermoelectric layers, and is in contact with the first insulating layer.

7. The thermoelectric conversion device according to claim **2**, wherein the fourth insulating layer is porous, and the third insulating layer is non-porous.

8. The thermoelectric conversion device according to claim **2**, wherein the fourth insulating layer is in contact with the first thermoelectric layers and the second thermoelectric layers, and is in contact with the third insulating layer.

9. The thermoelectric conversion device according to claim **8**,

wherein the second insulating layer is in contact with the first thermoelectric layers and the second thermoelectric layers, and is in contact with the first insulating layer,

wherein the thickness of the second insulating layer is equal to or less than twice the larger distance, and

wherein the thickness of the fourth insulating layer is equal to or less than twice the larger distance.

10. The thermoelectric conversion device according to claim **9**, wherein the thermal conductivity of the second insulating layer and the thermal conductivity of the fourth insulating layer are equal to or less than ⅕ times and equal to or greater than 1/100 times the thermal conductivity of the first insulating layer and the thermal conductivity of the second insulating layer.

11. The thermoelectric conversion device according to claim **10**, wherein the thermal conductivity of the second insulating layer and the thermal conductivity of the fourth insulating layer are equal to or less than 1/300 times and equal to or greater than 1/30000 times the thermal conductivities of the first connection layers, the second connection layers, the first thermally conductive layers, and the second thermally conductive layers.

12. The thermoelectric conversion device according to claim **11**, wherein the thermal conductivities of the first thermoelectric layers and the second thermoelectric layers are equal to or less than 1/50 times the thermal conductivities of the first connection layers, the second connection layers, the first thermally conductive layers, and the second thermally conductive layers.

13. The thermoelectric conversion device according to claim **12**, wherein the thermal conductivities of the first thermoelectric layers and the second thermoelectric layers are greater than the thermal conductivities of the second insulating layer and the fourth insulating layer.

14. The thermoelectric conversion device according to claim **2**, wherein the first insulating layer and the third insulating layer are HSQ layers or silicon oxide layers, and the second insulating layer and the fourth insulating layer are porous silica.

15. The thermoelectric conversion device according to claim **1**, wherein the first distance is the same as the second distance.

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