US 20150241136A1

(19) **United States**

(12) **Patent Application Publication**

MAEDA et al.

(10) **Pub. No.: US 2015/0241136 A1**

(43) **Pub. Date: Aug. 27, 2015**

(54) **HEAT STORAGE DEVICE AND METHOD OF USING LATENT HEAT STORAGE MATERIAL**

(71) Applicant: **Panasonic Intellectual Property Management Co., Ltd.**, Osaka (JP)

(72) Inventors: **SHIGENORI MAEDA**, Kyoto (JP); **TOYOJI GUSHIMA**, Osaka (JP); **TOSHIYASU TANAKA**, Osaka (JP); **HIRONORI TOMITA**, Nara (JP); **RENJI HONDA**, Nara (JP)

(21) Appl. No.: **14/615,388**

(22) Filed: **Feb. 5, 2015**

(30) **Foreign Application Priority Data**

Feb. 21, 2014 (JP) 2014-031348
Jul. 1, 2014 (JP) 2014-135785

Publication Classification

(51) **Int. Cl.**
F28D 20/02 (2006.01)

(52) **U.S. Cl.**
CPC ***F28D 20/02*** (2013.01)

(57) **ABSTRACT**

A heat storage device includes a pair of electrodes; an alternating-current power source that applies an alternating-current voltage to the pair of electrodes; and a latent heat storage material that is disposed between the pair of electrodes, a supercooled state of the latent heat storage material being maintained by the alternating-current voltage.

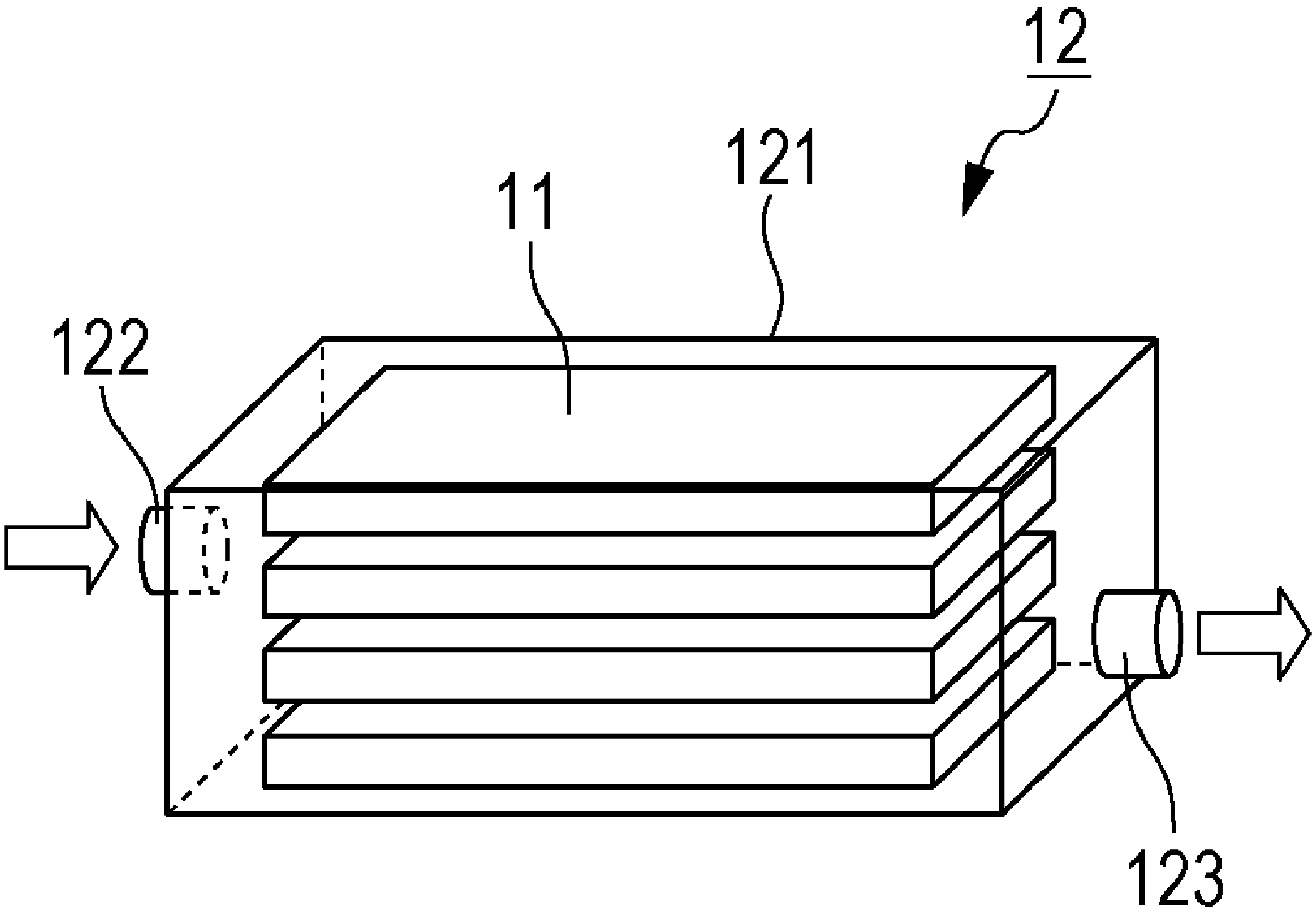


FIG. 1

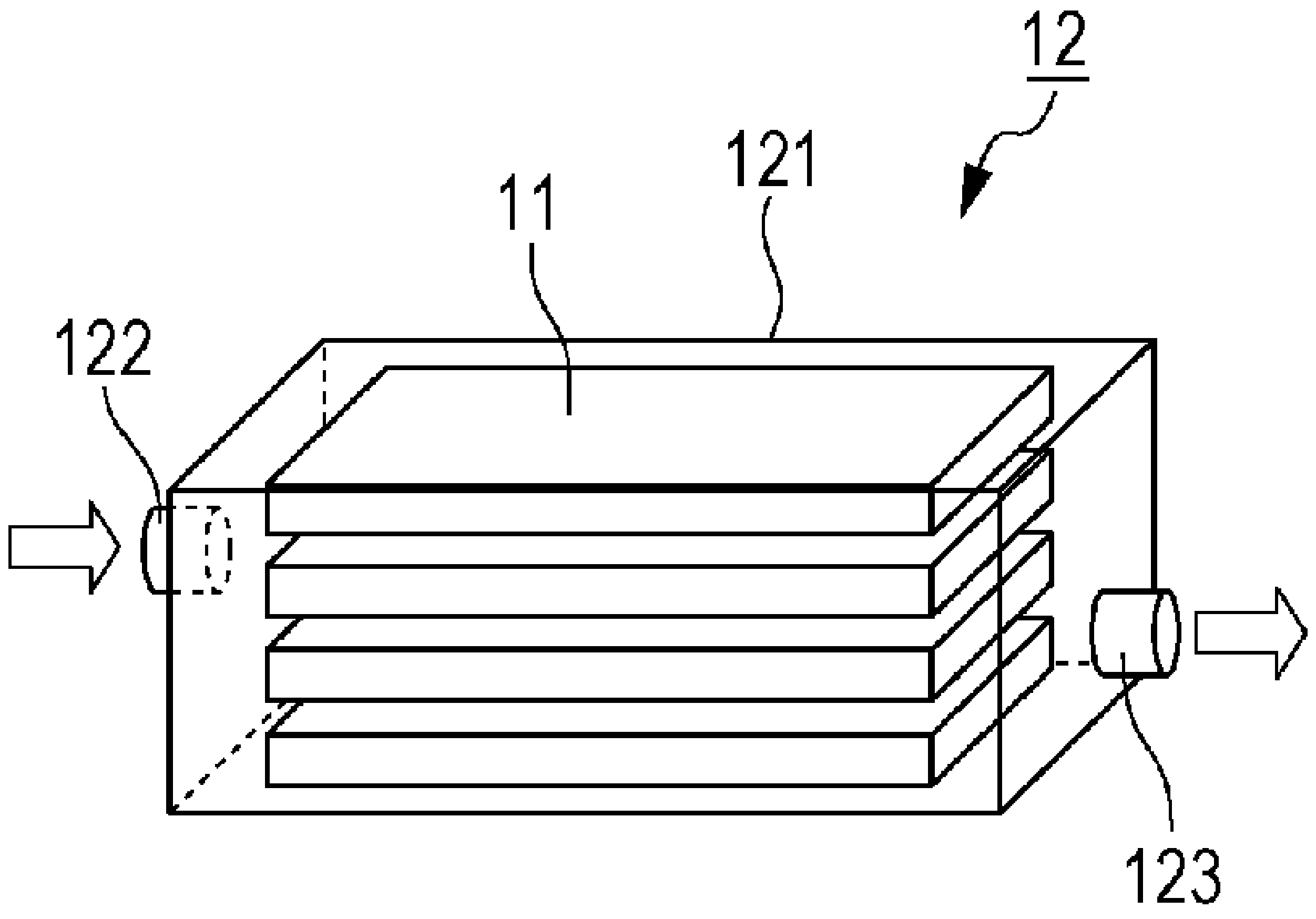

12
121
11
122
123

FIG. 2

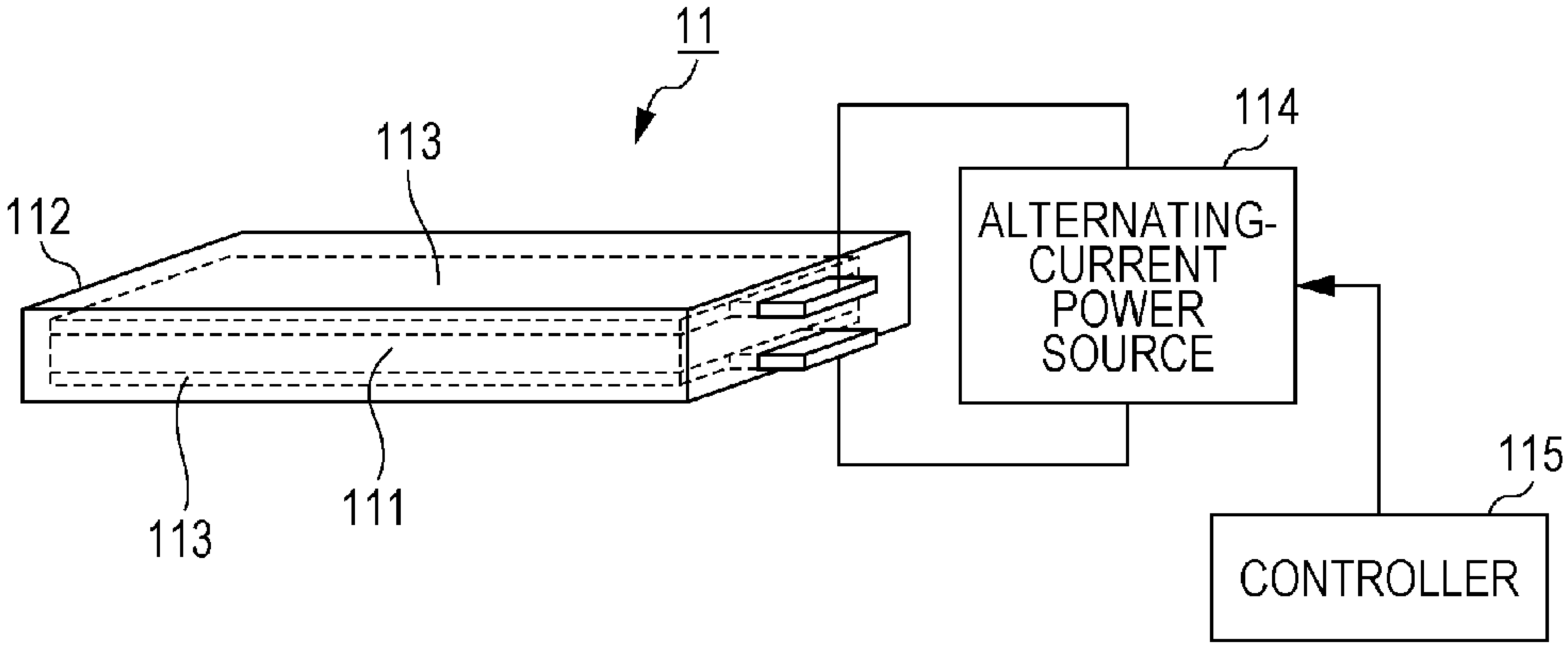

11
113
112
114
ALTERNATING-CURRENT POWER SOURCE
115
CONTROLLER
113
111

FIG. 3

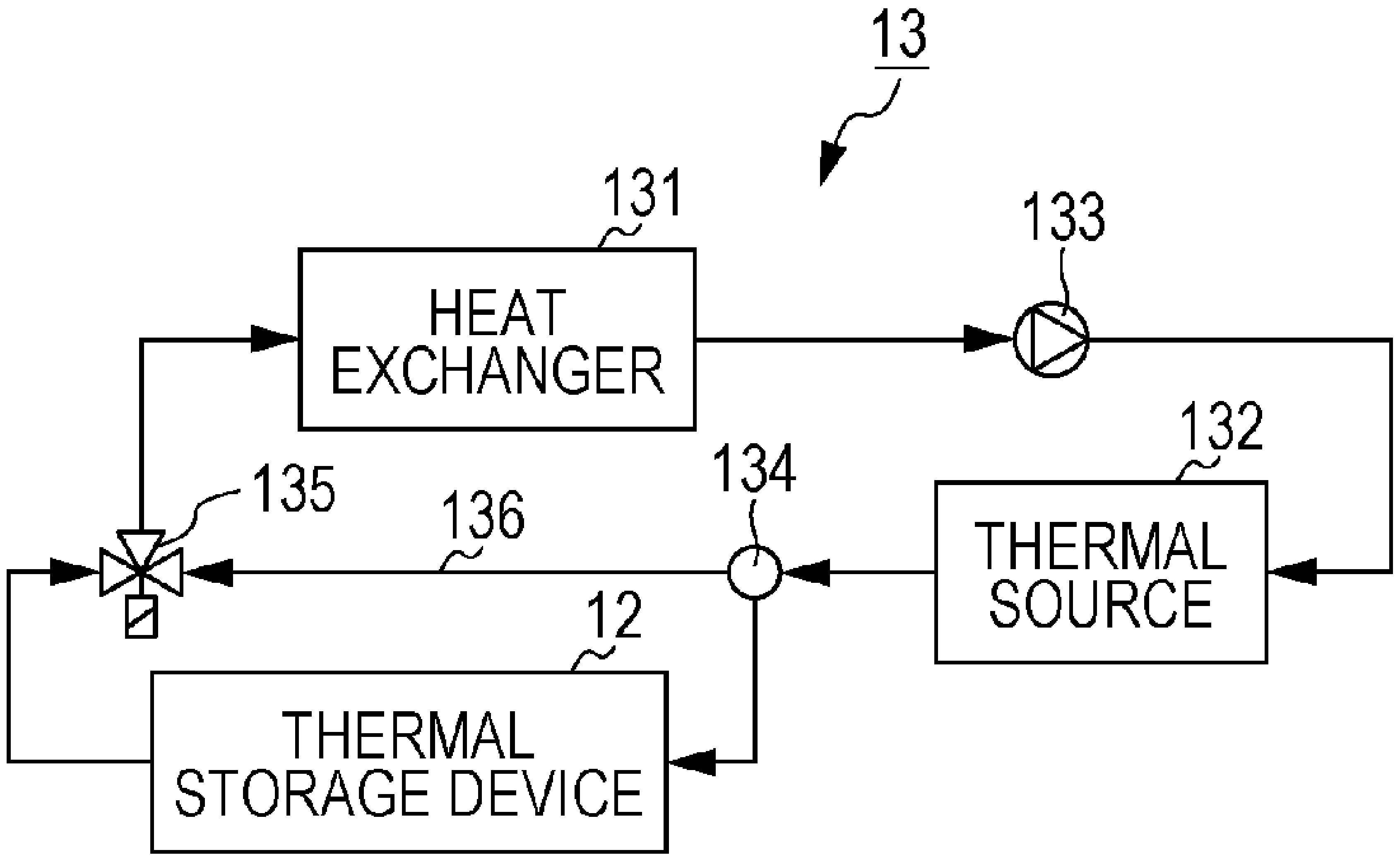


FIG. 4

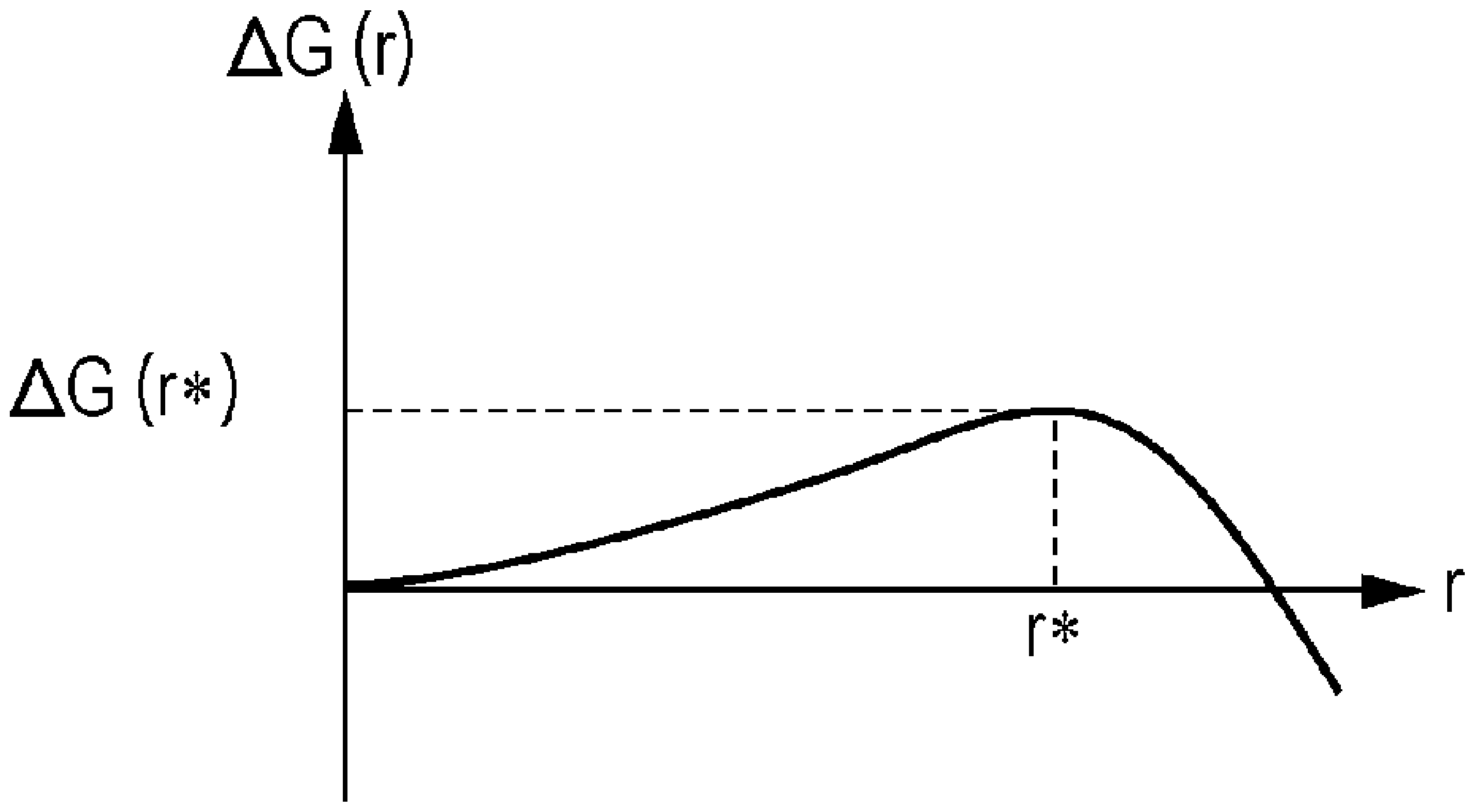


FIG. 5

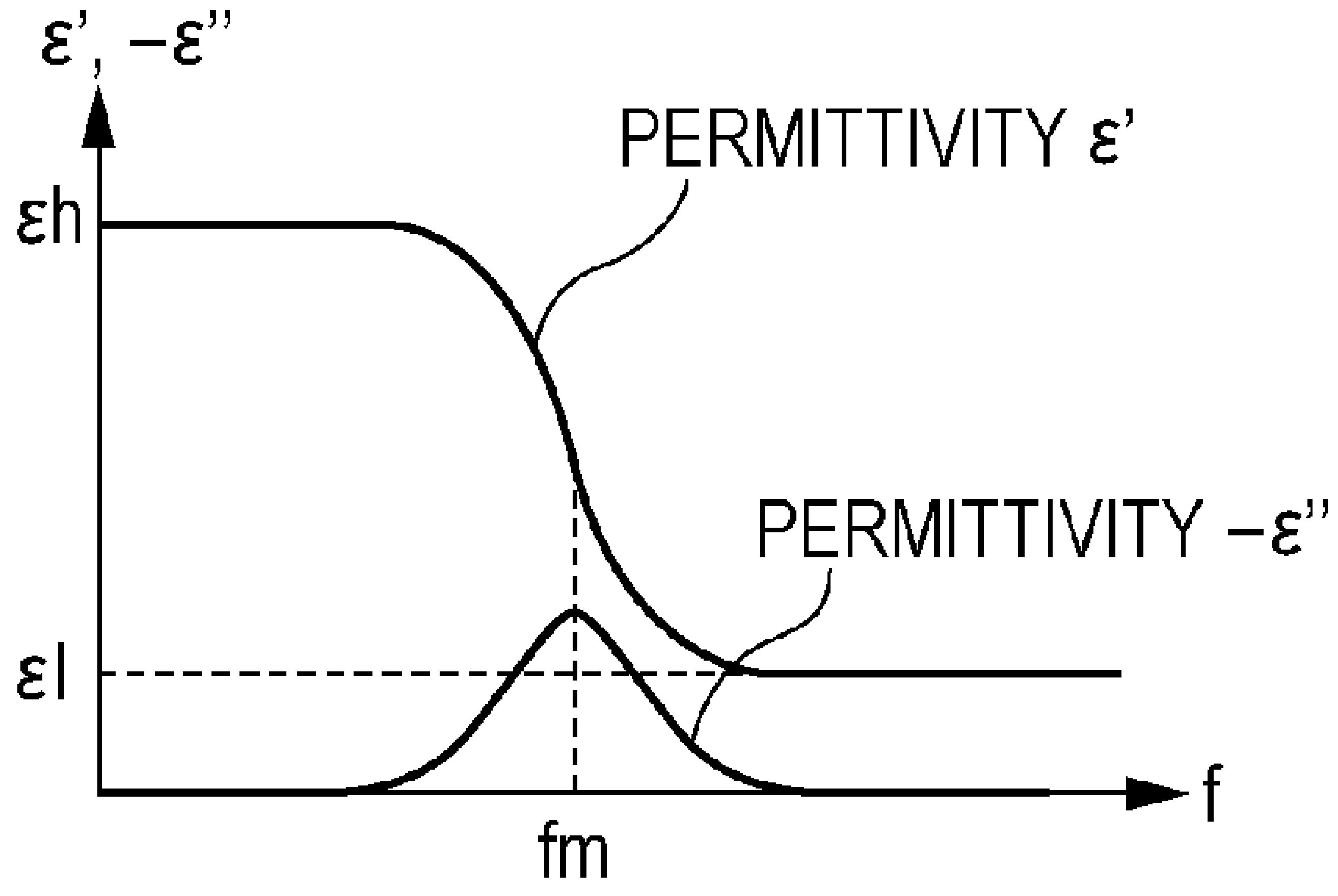


FIG. 6

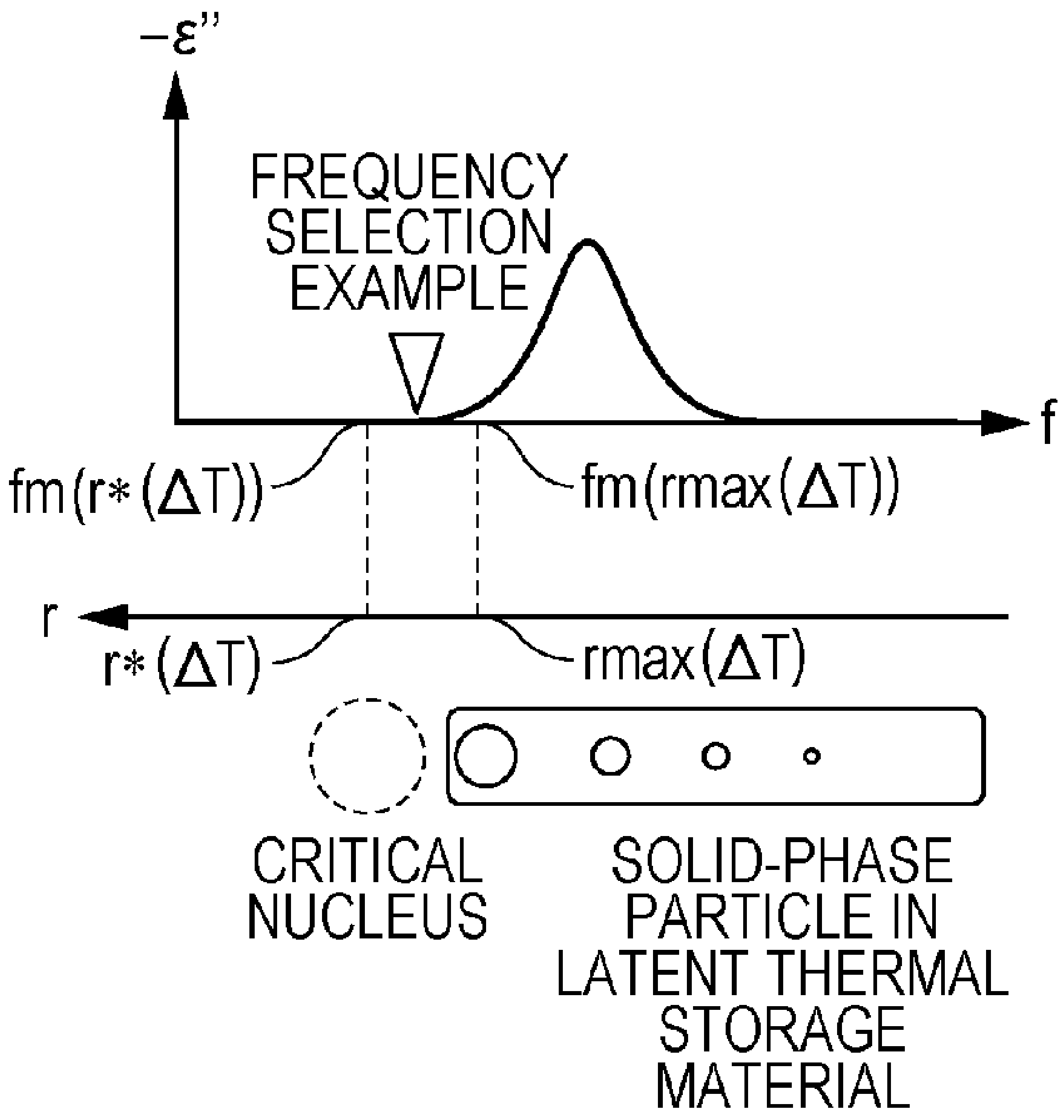

−ε"
FREQUENCY SELECTION EXAMPLE
f
fm(r*(ΔT))
fm(rmax(ΔT))
r
r*(ΔT)
rmax(ΔT)
CRITICAL NUCLEUS
SOLID-PHASE PARTICLE IN LATENT THERMAL STORAGE MATERIAL

FIG. 7

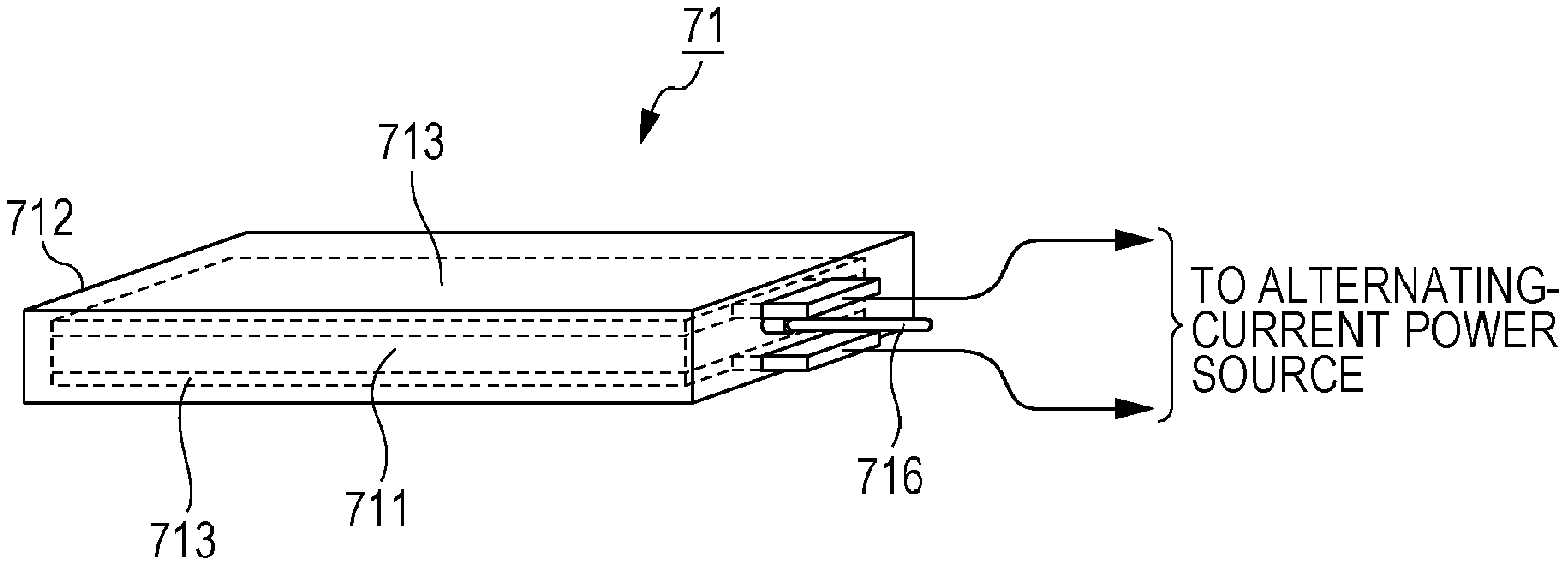

71
713
712
713
711
716
TO ALTERNATING-CURRENT POWER SOURCE

FIG. 8

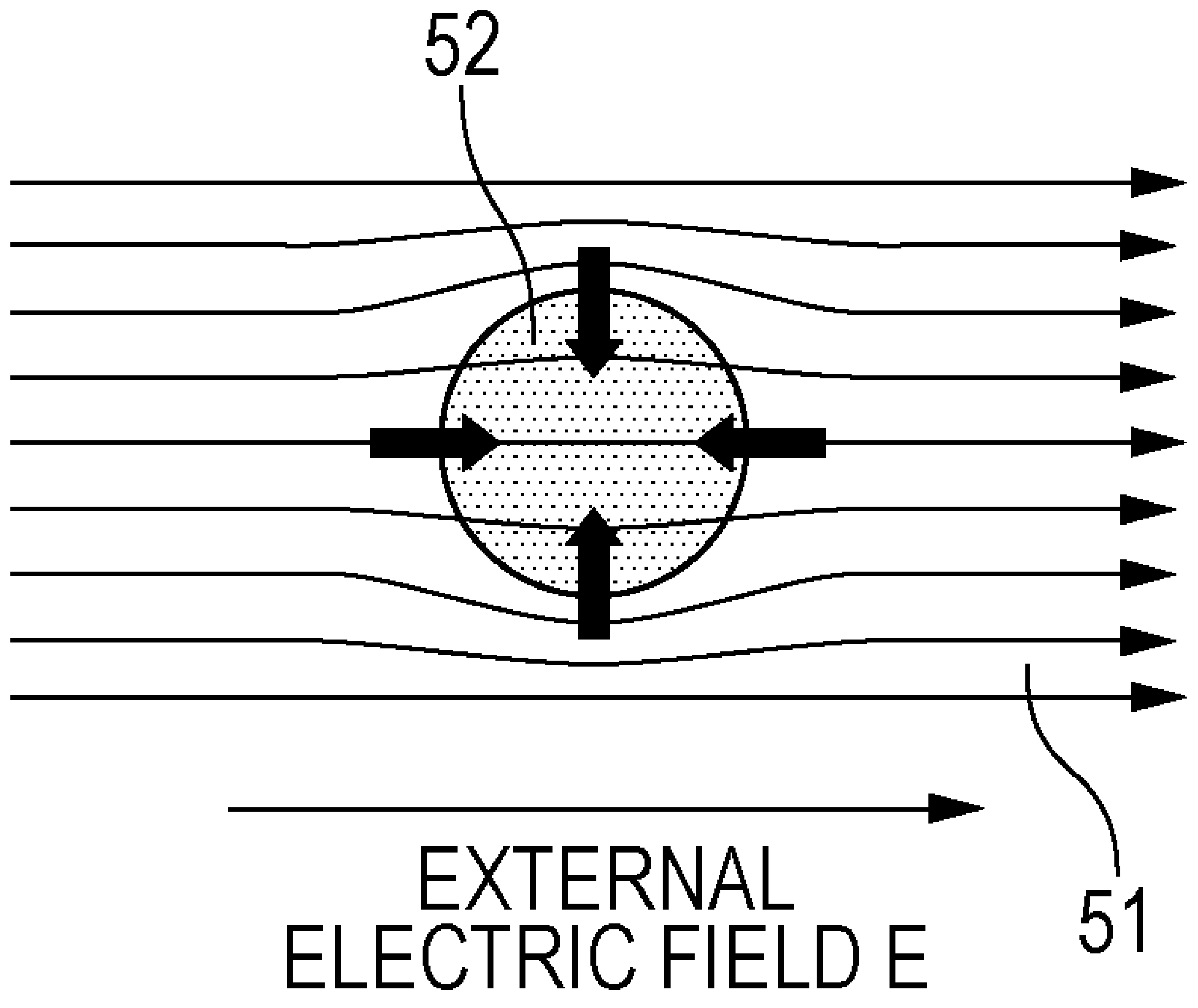

52
EXTERNAL
ELECTRIC FIELD E
51

FIG. 9

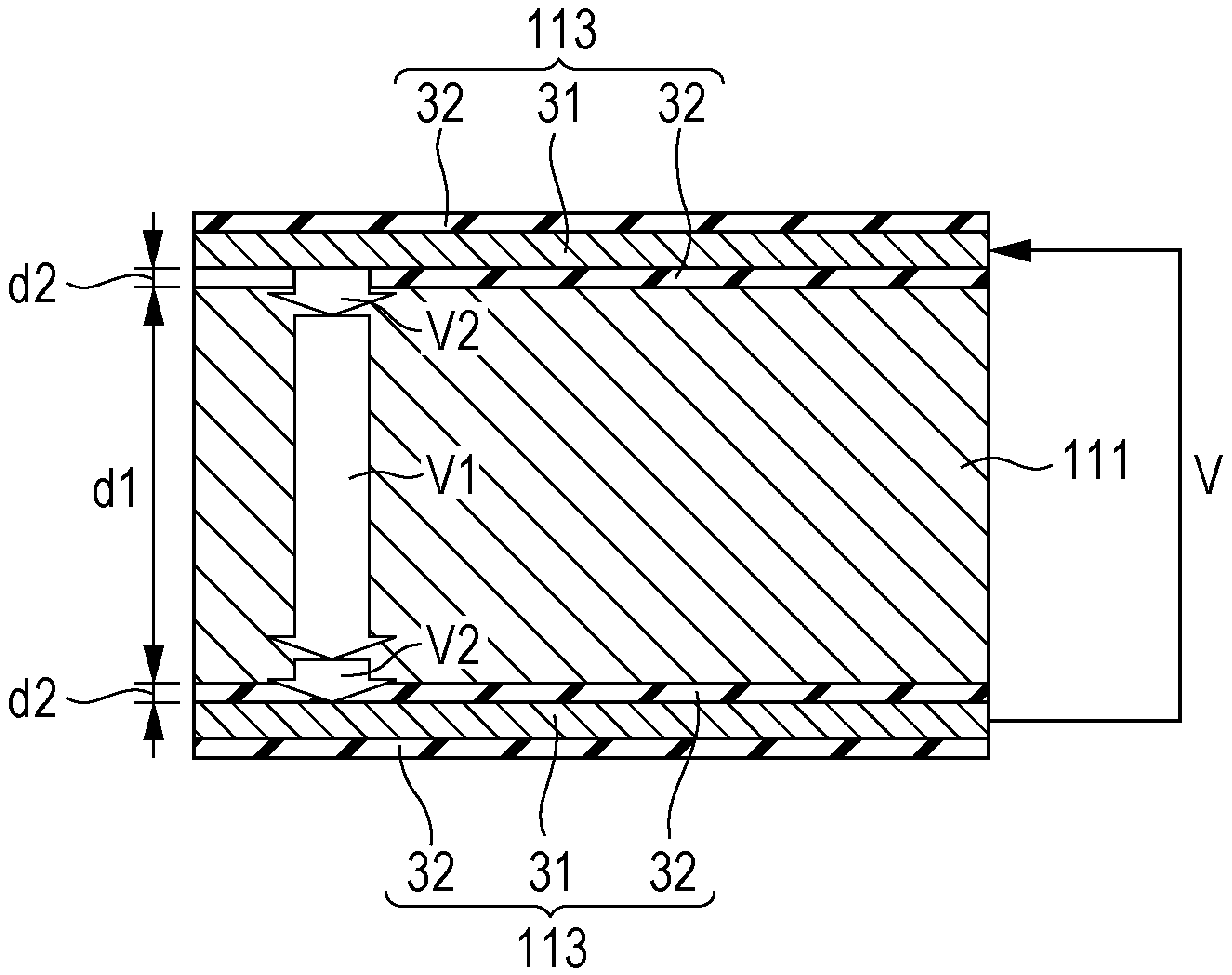

113
32
31
32
d2
V2
d1
V1
111
V
V2
d2
32
31
32
113

FIG. 10

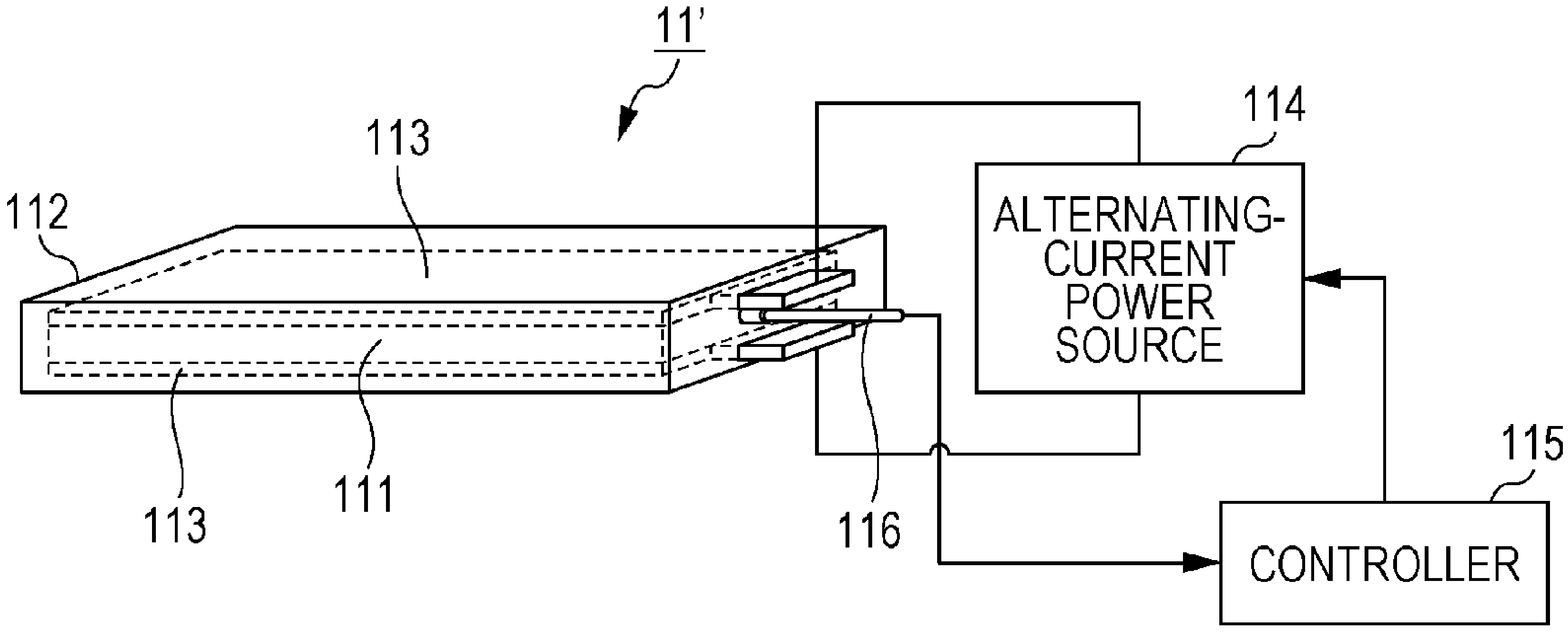
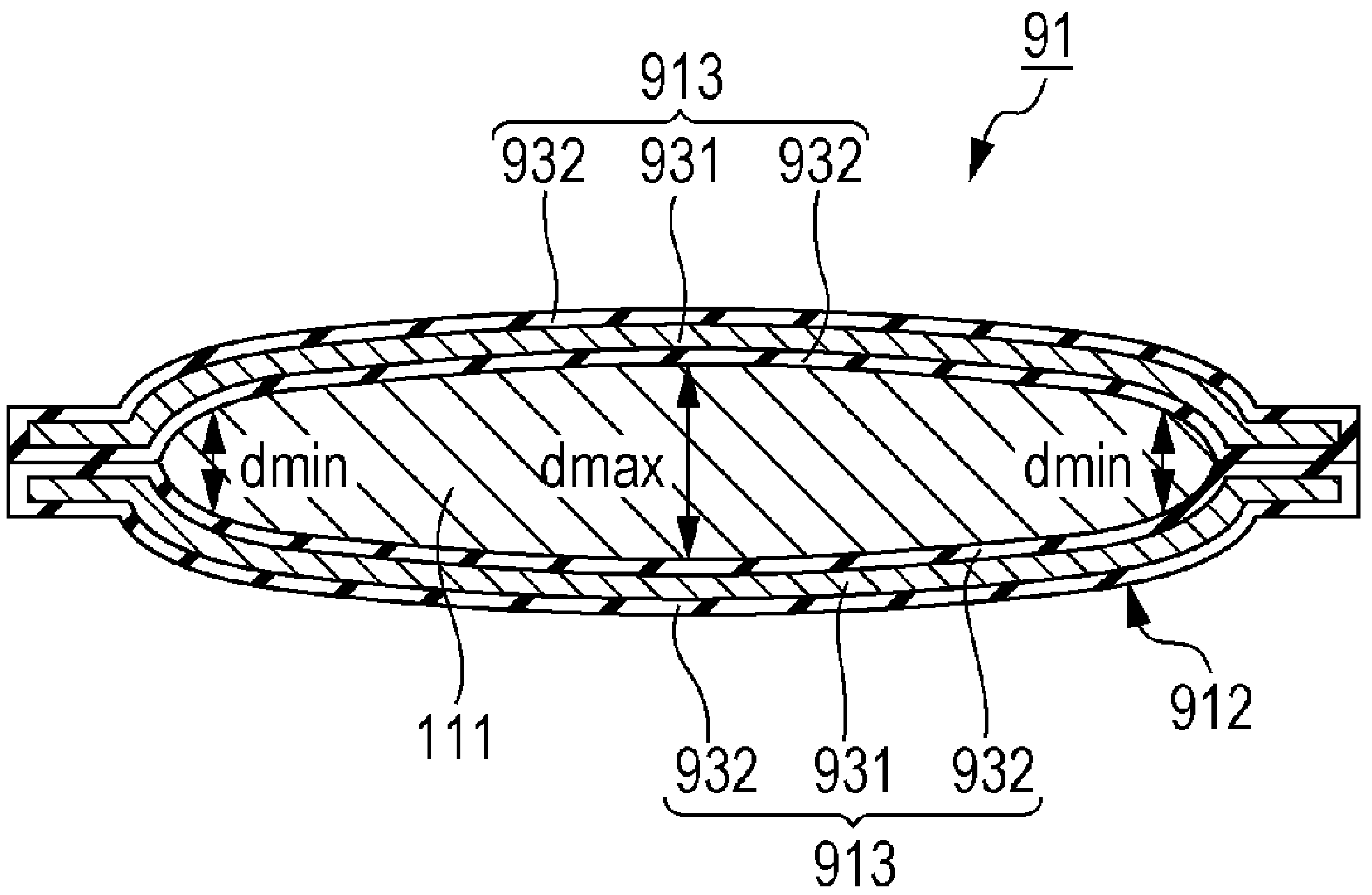

11'
113
112
114
ALTERNATING-CURRENT POWER SOURCE
115
CONTROLLER
113
111
116

FIG. 11


913
932
931
932
91
dmin
dmax
dmin
111
932
931
932
913
912

HEAT STORAGE DEVICE AND METHOD OF USING LATENT HEAT STORAGE MATERIAL

BACKGROUND

[0001] 1. Technical Field

[0002] The present disclosure relates to a heat storage device and a method of using a latent heat storage material.

[0003] 2. Description of the Related Art

[0004] Conventionally, as a heat storage medium, a latent heat storage material that absorbs or releases latent heat during phase transition between a solid phase and a liquid phase has been considered. One example of a latent heat storage material is sodium acetate trihydrate. Latent heat storage materials have a property of maintaining a liquid phase without undergoing a phase transition even below a freezing point, so-called supercooling.

[0005] Japanese Unexamined Patent Application Publication No. 2012-32130 discloses a supercooling control device that maintains supercooling by applying a direct-current negative voltage to a copper electrode whose tip has a plurality of V-shaped grooves, and that releases supercooling by applying an alternating-current voltage to the copper electrode.

SUMMARY

[0006] If the supercooled state of the latent heat storage material is maintained, heat can be stored for a long time. However, typically, supercooled state is unstable. In view of this, one non-limiting and exemplary embodiment provides a technique for stably maintaining a supercooled state of a latent heat storage material.

[0007] In one aspect, the techniques disclosed here feature a heat storage device including: a pair of electrodes; an alternating-current power source that applies an alternating-current voltage to the pair of electrodes; and a latent heat storage material that is disposed between the pair of electrodes, the latent heat storage material being maintained in a supercooled state by the alternating-current voltage.

[0008] According to the technique of the present disclosure, a supercooled state of the latent heat storage material can be stably maintained.

[0009] It should be noted that comprehensive or specific embodiments may be implemented as a system, a method, an integrated circuit, a computer program, a storage medium, or any selective combination thereof.

[0010] Additional benefits and advantages of the disclosed embodiments will become apparent from the specification and drawings. The benefits and/or advantages may be individually obtained by the various embodiments and features of the specification and drawings, which need not all be provided in order to obtain one or more of such benefits and/or advantages.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. **1** is a schematic view illustrating an example of a configuration of a heat storage device according to Embodiment 1;

[0012] FIG. **2** is a schematic view illustrating an example of a configuration of a heat storage unit according to Embodiment 1;

[0013] FIG. **3** is a schematic view illustrating an example of a configuration of an air heating device according to Embodiment 1;

[0014] FIG. **4** is a view illustrating an example of a relationship between a radius of a solid-phase particle and a free energy difference that is related to maintenance of a supercooled state;

[0015] FIG. **5** is a view illustrating an example of a relationship between a change of permittivity and a relaxation frequency at application of an alternating-current voltage to a dielectric;

[0016] FIG. **6** is a schematic view illustrating an example of a method for determining a frequency of an alternating-current voltage;

[0017] FIG. **7** is a schematic view illustrating a configuration of a test unit;

[0018] FIG. **8** is a schematic view illustrating a principle of crystallization inhibiting power by an external electric field;

[0019] FIG. **9** is a schematic view illustrating an example of a configuration of a heat storage unit according to Embodiment 2;

[0020] FIG. **10** is a schematic view illustrating an example of a configuration of a heat storage unit according to Embodiment 3; and

[0021] FIG. **11** is a schematic view illustrating an example of a configuration of a heat storage unit according to Embodiment 4.

DETAILED DESCRIPTION

[0022] A heat storage device according to one aspect of the present disclosure includes a pair of electrodes, an alternating-current power source that applies an alternating-current voltage to the pair of electrodes, and a latent heat storage material that is disposed between the pair of electrodes, the latent heat storage material being maintained in a supercooled state by the alternating-current voltage.

[0023] This enables the latent heat storage material to stably maintain the supercooled state.

[0024] In the heat storage device according to one aspect of the present disclosure, for example, each of the pair of electrodes may include an electrode main body having electrical conductivity and an insulation layer coating a surface of the electrode main body. This makes it possible to prevent the electrodes from corroding due to the latent heat storage material.

[0025] In the heat storage device according to one aspect of the present disclosure, for example, the alternating-current voltage may be in a range of 2 V to 35 V. This makes it possible to not only maintain the supercooled state of the latent heat storage material, but also prevent electrolysis of the latent heat storage material.

[0026] In the heat storage device according to one aspect of the present disclosure, for example, a frequency of the alternating-current voltage may be in a range of 10 kHz to 100 kHz. This makes it possible to stably maintain the supercooled state of the latent heat storage material.

[0027] In the heat storage device according to one aspect of the present disclosure, for example, the alternating-current power source may apply the alternating-current voltage to the pair of electrodes to maintain the supercooled state of the latent heat storage material, and then further may stop application of the alternating-current voltage to release the supercooled state of the latent heat storage material. This allows the latent heat to be released from the latent heat storage material.

[0028] The heat storage device according to one aspect of the present disclosure, for example, further may include a temperature sensor that directly or indirectly detects a temperature of the latent heat storage material. The alternating-current power source may include a variable frequency power source. The frequency of the alternating-current voltage may be changed in accordance with the detected temperature. This makes it possible to apply an alternating-current voltage having an optimum frequency to the electrodes in accordance with the temperature of the latent heat storage material. As a result, it is possible to more stably maintain the supercooled state of the latent heat storage material.

[0029] The heat storage device according to one aspect of the present disclosure, for example, further may include a temperature sensor that directly or indirectly detects a temperature of the latent heat storage material. The alternating-current power source may include a variable voltage power source. The alternating-current voltage may be changed in accordance with the detected temperature. This makes it possible to apply an alternating-current voltage having an optimum voltage peak value to the electrodes in accordance with the temperature of the latent heat storage material. As a result, it is possible to more stably maintain the supercooled state of the latent heat storage material.

[0030] The heat storage device according to one aspect of the present disclosure, for example, further may include a temperature sensor that directly or indirectly detects a temperature of the latent heat storage material. The alternating-current power source may select whether or not the alternating-current voltage is applied to the pair of electrodes in accordance with the detected temperature. This makes it possible to apply an alternating-current voltage at an optimum timing in accordance with the temperature of the latent heat storage material. As a result, it is possible to more stably maintain the supercooled state of the latent heat storage material.

[0031] In the heat storage device according to one aspect of the present disclosure, for example, in a case where the temperature of the latent heat storage material is higher than a freezing point of the latent heat storage material, the alternating-current power source may not apply the alternating-current voltage to the pair of electrodes, and in a case where the temperature of the latent heat storage material is equal to or lower than the freezing point of the latent heat storage material, the alternating-current power source may apply the alternating-current voltage to the pair of electrodes. This makes it possible to save consumed electric power.

[0032] In the heat storage device according to one aspect of the present disclosure, for example, after heat has been applied to the latent heat storage material from outside of the heat storage device, the alternating-current power source may apply the alternating-current voltage to the pair of electrodes to maintain the supercooled state of the latent heat storage material.

[0033] In the heat storage device according to one aspect of the present disclosure, for example, the latent heat storage material may contain a hydrated salt or sugar alcohol.

[0034] In the heat storage device according to one aspect of the present disclosure, for example, the latent heat storage material may be sodium acetate trihydrate. Since sodium acetate trihydrate has a freezing point (58° C.) and an amount of latent heat (250 J/g), sodium acetate trihydrate is suitable for the heat storage device.

[0035] A method according to one aspect of the present disclosure of using a latent heat storage material includes applying heat to a latent heat storage material disposed between a pair of electrodes to melt the latent heat storage material; after the melted latent heat storage material enters a supercooled state, applying an alternating-current voltage to the pair of electrodes to maintain the supercooled state of the latent heat storage material while the latent heat storage material retains the heat; and stopping application of the alternating-current voltage to release the supercooled state of the latent heat storage material, allowing the heat to be released from the latent heat storage material. This makes it possible to stably maintain the supercooled state of the latent heat storage material.

[0036] Embodiments of the present disclosure are described below with reference to the drawings. Note that each of the embodiments below illustrates a comprehensive or specific example. Numeric values, expressions, theoretical models, shapes, materials, constituent elements, positions and connection forms of the constituent elements, steps, the order of the steps, and the like are merely examples, and are not intended to limit the present disclosure. Out of the constituent elements described in the embodiments below, constituent elements that are not described in independent claims that recite the highest concepts are described as optional constituent elements.

[0037] In all of the drawings mentioned below, identical or equivalent parts are given identical reference numerals, and overlapping description of such parts may be omitted.

Embodiment 1

Configuration

[0038] As illustrated in FIG. **1**, a heat storage device **12** according to Embodiment 1 includes a plurality of heat storage units **11** and a chassis **121** in which the plurality of heat storage units **11** are contained. The plurality of heat storage units **11** are, for example, stacked at constant intervals in the chassis **121**. The chassis **121** includes a heating medium inlet **122** through which a heating medium flows in and a heating medium outlet **123** through which the heating medium flows out. Heat is exchanged between the heating medium and the plurality of heat storage units **11**. In the heat storage device **12**, the heat exchange can be easily performed. Examples of the heating medium include water, brine, and oil.

[0039] As illustrated in FIG. **2**, each of the plurality of heat storage units **11** includes a container **112** and a latent heat storage material **111** that fills the container **112**. The container **112** may have a high heat conductive property. This can improve the heat conductivity of the heat storage units **11**. The container **112** may be made of a material having a high heat conductive property such as aluminum, copper, graphite, or a high heat conductive resin or may be made of other materials. The container **112** has, for example, a hollow structure having a thickness of approximately 10 mm. The inside of the hollow structure is filled with the latent heat storage material **111**. Furthermore, the container **112** includes a pair of counter electrodes **113** provided on two opposite surfaces thereof. The pair of counter electrodes **113** are in contact with the latent heat storage material **111** that fills the container **112**. To be more specific, the latent heat storage material **111** is disposed between the pair of counter electrodes **113**. The counter electrodes **113** are electrically connected to an alternating-current power source **114**. The alternating-current power source **114**, for example, applies, between the pair of counter electrodes **113**, an alternating-current voltage having a frequency determined by a controller **115**. By application of the alternating-current voltage between the counter electrodes **113**, the latent heat storage material **111** can maintain a supercooled state.

[0040] The latent heat storage material **111** is made of a material that maintains a supercooled state upon application of a predetermined alternating-current voltage. The latent heat storage material **111** is, for example, a dielectric containing polar molecules. The latent heat storage material **111** contains, for example, a substance other than tap water and purified water. Examples of main ingredients of the latent heat storage material **111** include hydrated salts such as sodium acetate trihydrate, sodium sulfate decahydrate, disodium hydrogen phosphate dodecahydrate, sodium carbonate decahydrate, and sodium thiosulfate pentahydrate and sugar alcohols such as mannitol, erythritol, and D-threitol. In the present disclosure, the term "main ingredients" refers to, for example, ingredients contained in an amount of 60% or more by weight. The latent heat storage material **111** is, for example, sodium acetate trihydrate. Sodium acetate trihydrate is suitable for the heat storage device **12** because sodium acetate trihydrate has a freezing point (58° C.) and a large amount of latent heat (250 J/g).

[0041] Each of the counter electrodes **113**, for example, includes an electrode main body having electrical conductivity and an insulation layer coating a surface of the electrode main body. The counter electrodes **113** may be insulated from the latent heat storage material **111**. This makes it possible to prevent the counter electrodes **113** from corroding due to the latent heat storage material **111** at voltage application. The insulation layer can be formed by attaching a resin film on the surface of the electrode main body or applying a solution containing an insulator to the surface of the electrode main body.

[0042] The heat storage device **12** or the heat storage units **11** may not include a special member for releasing the supercooled state. In this case, for example, the supercooled state is released by stopping application of the alternating-current voltage for maintaining the supercooled state to the counter electrodes **113**. Alternatively, the supercooled state may be released by applying, to the counter electrodes **113**, a voltage different from the alternating-current voltage for maintaining the supercooled state. The voltage for releasing the supercooled state can be an alternating-current voltage that has a different frequency and/or a different voltage peak value from the alternating-current voltage for maintaining the latent heat storage material **111** in the supercooled state. The voltage for releasing the supercooled state may be a direct-current voltage.

[0043] In a case where the latent heat storage material **111** has a property of easily shifting into a supercooled state, the heat storage device **12** or the heat storage units **11** may have supercooling releasing means (not illustrated). The supercooling releasing means may be, for example, an ultrasonic vibrator that is disposed in the container **112** and that has a portion which is immersed in the latent heat storage material **111**. The ultrasonic vibrator can release the supercooled state of the latent heat storage material **111** by providing ultrasonic vibration of a predetermined frequency to the latent heat storage material **111**. Alternatively, the supercooling releasing means may be, for example, a Peltier device that is provided in contact with the latent heat storage material **111**. When a voltage is applied to the Peltier device, a surface of the Peltier device that is in contact with the latent heat storage material **111** is cooled, and thereby the supercooled state of the latent heat storage material **111** can be released. Alternatively, the supercooling releasing means may be, for example, a needle-like metal object that protrudes into the latent heat storage material **111** in the container **112**. When the needle-like metal object enters the latent heat storage material **111**, the supercooled state of the latent heat storage material **111** can be released.

[0044] FIG. **3** illustrates an example of a configuration of an air heating device **13** that includes the heat storage device **12**. As illustrated in FIG. **3**, the air heating device **13** includes the heat storage device **12**, a heat source **132** that supplies heat to the heat storage device **12**, and a heat exchanger **131** that releases heat from the heat storage device **12** and the heat source **132**. The air heating device **13** may further include a pump **133**, a bypass pipe **136**, a flow divider **134**, and a mixing valve **135**. The heat exchanger **131** transmits heat from a heating medium of high temperature to air. The pump **133** circulates the heating medium. The heat source **132** heats the heating medium. The heat storage device **12** absorbs and stores heat when the temperature thereof is lower than that of the heating medium flowing thereinto, and releases heat when the temperature thereof is higher than that of the heating medium. The flow divider **134** and the mixing valve **135** controls the amount of heating medium that flows into the heat storage device **12** and the amount of heating medium that flows into the bypass pipe **136**. The heat source **132** may be, for example, an electric heater, a heat pump, an internal-combustion engine, or the like.

[Frequency of Alternating-Current Voltage]

[0045] The following describes why an alternating-current voltage having a predetermined frequency allows a latent heat storage material to maintain a supercooled state.

[0046] The supercooled state of the latent heat storage material corresponds to a metastable state of free energy. FIG. **4** illustrates an example of a relationship between a radius of a solid-phase particle and a free energy difference. The vertical axis of FIG. **4** represents a free energy difference ΔG (r) obtained by subtracting free energy of a liquid phase from free energy of a solid phase. The horizontal axis of FIG. **4** represents a radius r of a solid-phase particle present in the liquid phase. The term "solid-phase particle" refers to a nucleus formed by bonding molecules, ions, or both of them in a liquid phase of the latent heat storage material. As illustrated in FIG. **4**, the free energy difference ΔG has a maximum value ΔG (r*) when the radius r of the solid-phase particle has a critical nucleus radius r*. In a case where the radius r of the solid-phase particle is smaller than the critical nucleus radius r*, the latent heat storage material maintains a supercooled state, which is a metastable state. When the free energy of the solid-phase particle exceeds an energy barrier ΔG (r*) due to fluctuation, the radius r of the solid-phase particle exceeds the critical nucleus radius r*. As a result, the solid-phase particle grows, and the whole latent heat storage material shifts from a liquid phase to a solid phase. The maximum value ΔG (r*) of the free energy difference and the critical nucleus radius r* may be given, for example, by the following expression (1):

$$\Delta G(r^*) = \frac{16\pi\sigma^3 (T_e)^2}{3(\Delta H\rho)^2(\Delta T)^2} \tag{1}$$

-continued

$$r^* = \frac{2\sigma T_e}{\Delta H \rho \Delta T}$$

[0047] where σ is solid-liquid interfacial tension, Te is a solid-liquid equilibrium temperature, ΔH is the amount of latent heat per unit mass, and ρ is density. These values are determined by physical properties of the latent heat storage material. In the present disclosure, for simplification of the description, the solid-liquid equilibrium temperature is sometimes referred to as a freezing point. AT is the degree of supercooling obtained by subtracting the temperature of the latent heat storage material from the freezing point. As illustrated in FIG. **4** and expression (1), as the degree of supercooling ΔT increases, ΔG (r*) and r* decrease. That is, as the temperature decreases, it becomes more difficult to maintain the supercooled state.

[0048] Since the latent heat storage material is a dielectric, the latent heat storage material has dielectric dispersion. FIG. **5** illustrates an example of a relationship between the permittivity of the latent heat storage material and the frequency of the alternating-current voltage. In FIG. **5**, permittivity ∈' is close to permittivity ∈h when the frequency f is low, whereas the permittivity ∈' is close to permittivity ∈l when the frequency f is high. That is, the permittivity ∈' exhibits so-called relaxation-type dielectric dispersion. As illustrated in FIG. **5**, as the frequency increases, the permittivity ∈' decreases. This is because the orientation of molecules, ions, or solid-phase particles in the liquid phase of the latent heat storage material is unable to follow the variation of an alternating-current electric field. In FIG. **5**, when an alternating-current voltage of a relaxation frequency fm is applied to the latent heat storage material in a supercooled state, the orientation of the molecules, ions, or solid-phase particles in the liquid phase of the latent heat storage material is severely disturbed. The degree of disorder of the orientation is related to the magnitude of dielectric loss ∈" in FIG. **5**. When the alternating-current electric field disturbs the orientation of the molecules, ions, or solid-phase particles in the liquid phase, bonding of these particles is hindered, and thereby growth of the solid-phase particle into a critical nucleus is hindered. In other words, by applying a predetermined alternating-current voltage to the latent heat storage material, the supercooled state of the latent heat storage material can be maintained.

[0049] A relaxation frequency at which an effect of disturbing the orientation of the solid-phase particles becomes maximum may be, for example, calculated by the following expression (2):

$$f_m = \frac{kT}{4\pi r^3 \eta} \tag{2}$$

[0050] where k is the Boltzmann constant, T is a temperature, η is the viscosity of the melt of the latent heat storage material, and r is the radius of a target particle. As illustrated in expression (2), as the radius r of the target solid-phase particle decreases, the relaxation frequency that disturbs the orientation of the particles increases. Accordingly, the relaxation frequency fm of the alternating-current voltage may be a frequency that corresponds to the maximum radius r of the solid-phase particle contained in the latent heat storage material in a supercooled state. Alternatively, the relaxation frequency fm of the alternating-current voltage may be a frequency that corresponds to the critical nucleus radius r*. This can maximize the effect of maintaining the supercooled state of the latent heat storage material.

[0051] The critical nucleus radius r* varies depending on the properties of the latent heat storage material and the temperature of the latent heat storage material.

[0052] An example of a method for determining the frequency of the alternating-current voltage by using expressions (1) and (2) is described below.

[0053] First, the critical nucleus radius r* (ΔT) is determined on the basis of expression (1). The parameters of expression (1) are determined as follows. In a case where the latent heat storage material **111** is sodium acetate trihydrate, the amount of latent heat AH per unit mass, the freezing point Te, and the liquid phase density ρ are determined, for example, by referring to CRIEPI Research Report No. M05010 ("Development of new phase change materials—Research on thermal storage technologies and study for target thermophysical properties of phase change materials—", Leaflet, page **2**, table **2**, **2006**). The solid-liquid interfacial tension σ may be determined from the nucleation speed J [1/s] measured by experiments and from expressions (1) and (3). The degree of supercooling ΔT is, for example, a difference obtained by subtracting the lowest outside air temperature from the freezing point of the latent heat storage material **111**.

$$J = \frac{1000\rho NVkT}{\eta M}\exp\left(-\frac{\Delta G(r^*)f(\theta)}{kT}\right) \tag{3}$$

$$f(\theta) = \frac{(2+\cos\theta)(1-\cos\theta)^2}{4}$$

[0054] where θ is the wetting angle between the container **112** and the latent heat storage material **111**, V is the volume of the latent heat storage material **111**, M is the mass number of the latent heat storage material **111**, n is Avogadro's number, and k is the Boltzmann constant.

[0055] Second, the relaxation frequency fm (r* (ΔT)) of the critical nucleus is determined on the basis of the critical nucleus radius r* (ΔT) and expression (2). The viscosity coefficient of the latent heat storage material **111** is determined, for example, by measurement.

[0056] According to this calculation method, in a case where sodium acetate trihydrate is maintained in a supercooled state at an outside air temperature of −20° C., the relaxation frequency fm (r* (ΔT)) is, for example, 38 kHz. Note that in this calculation, the solid-liquid interfacial tension σ is set to 8.85×10^{-2} N/m, the viscosity coefficient η is set to 0.5 Pa·s, and the other physical property values are set by referring to CRIEPI Research Report mentioned above.

[0057] In a case where the heat storage device **12** is maintained in a supercooled state at the lowest outside air temperature, it is considered that the latent heat storage material **111** does not contain a solid-phase particle having a radius equal to or larger than the critical nucleus radius r*. Therefore, the relaxation frequency may be a frequency fm (rmax (ΔT)) that corresponds to a maximum radius rmax (ΔT) of a solid-phase particle actually contained in the latent heat storage material in the supercooled state. Alternatively, as illustrated in FIG. **6**, the frequency of the alternating-current voltage may be a value in a range of fm (r* (ΔT)) to fm (rmax (ΔT)). The frequency of the alternating-current voltage may be, for example, an intermediate value between fm (r* (ΔT)) and fm (rmax (ΔT)) or an average of fm (r* (ΔT)) and fm (rmax (ΔT)). The value of fm (rmax (ΔT)) is, for example, corresponded to a low-frequency wave side end point of a peak of dielectric loss ∈" obtained by measurement of dielectric relaxation.

[0058] Note that the frequency of the alternating-current voltage is not limited to those described above. The frequency may be, for example, in a range of 10 kHz to 100 kHz. A voltage peak value of the alternating-current voltage may be, for example, in a range of 40 mV to 1.2 V. A method for determining the frequency of the alternating-current voltage is not limited to the above method. The frequency of the alternating-current voltage in the present disclosure is not limited to a specific one, provided that the frequency of the alternating-current voltage is one that allows the latent heat storage material to maintain a supercooled state. The frequency may be determined by using another theoretical formula or may be determined by using an experimental formula. The frequency may be determined without using any formula, and may be determined by using a table in which predetermined parameters and associated frequencies are listed. The frequency can be determined by using an empirical method or a semi-empirical method.

[Driving Method]

[0059] An example of a method for driving the air heating device **13** including the heat storage device **12** in Embodiment 1 is described below. The air heating device **13** and/or the heat storage device **12** operates in any one of a plurality of modes including a heat storage mode, a heat retention mode, and a heat release mode. Specific examples of the heat storage mode, the heat retention mode, and the heat release mode are described below.

[0060] The heat storage mode of the air heating device **13** is described first. In the heat storage mode, the heat source **132** and the pump **133** operate, and the mixing valve **135** is set so that all of the heating medium flows inside the heat storage device **12**. The temperature of the heating medium is raised to a temperature higher than the freezing point of the latent heat storage material **111** by the heat source **132**, and the latent heat storage material **111** stores heat from the heating medium as latent heat. After all of the latent heat storage material **111** melts, the mixing valve **135** may be controlled so that all of the heating medium flows in the bypass pipe **136** and so that the heating medium does not flow in the heat storage device **12**. This completes the heat storage mode. Whether or not all of the latent heat storage material **111** has melted may be determined, for example, by the temperature of the heating medium that flows out from the heating medium outlet **123** of the heat storage device **12**. For example, in a case where a predetermined time has elapsed from a timing at which the temperature of the heating medium in the heating medium outlet **123** exceeds the freezing point of the latent heat storage material **111**, it may be determined that all of the latent heat storage material **111** has melted. The heat source **132** illustrated in FIG. **3** may be, for example, an engine of an automobile. In this case, for example, during a period in which the engine is in operation, cooling water which is the heating medium circulates between the engine and the heat storage device **12**. Consequently, exhaust heat of the engine is stored in the heat storage device **12**.

[0061] Next, the heat retention mode of the air heating device **13** is described. The heat retention mode is executed after completion of the heat storage mode. In the heat retention mode, the alternating-current power source **114** starts applying, between the pair of counter electrodes **113** provided in each of the heat storage units **11**, an alternating-current voltage having a frequency that is preset in the controller **115**. This maintains a supercooled state of the latent heat storage material **111** even if the temperature of the latent heat storage material **111** decreases to an outside air temperature.

[0062] A timing at which the alternating-current power source **114** starts applying the alternating-current voltage to the counter electrodes **113** is not limited in particular. For example, the alternating-current power source **114** applies the alternating-current voltage to the counter electrodes **113** immediately after completion of the heat storage mode. According to this method, it is unnecessary to keep checking the state of the latent heat storage material **111** by using a sensor or the like. This makes it easy to control the heat storage device **12**. For example, it may be determined, on the basis of stoppage of the operation of the heat source **132**, that the heat storage mode has been completed. For example, in a case where the heat source **132** illustrated in FIG. **3** is an engine of an automobile, it may be determined, on the basis of input of a command to turn off the engine to an ECU (electric control unit) of the automobile, that the heat storage mode has been completed.

[0063] Whether or not the alternating-current voltage is applied to the counter electrodes **113** may be determined in accordance with the state of the latent heat storage material **111**. For example, in a case where the latent heat storage material **111** is not in a supercooled state, the alternating-current voltage is not applied between the counter electrodes **113**, whereas in a case where the latent heat storage material **111** is in a supercooled state, the alternating-current voltage is applied between the counter electrodes **113**. In other words, in a case where the temperature of the latent heat storage material **111** is higher than the freezing point of the latent heat storage material **111**, the alternating-current power source **114** does not apply the alternating-current voltage between the counter electrodes **113**, whereas in a case where the temperature of the latent heat storage material **111** is equal to or lower than the freezing point of the latent heat storage material **111**, the alternating-current power source **114** applies the alternating-current voltage between the counter electrodes **113**. According to this method, electric power consumption can be saved.

[0064] Next, the heat release mode of the air heating device **13** is described. In the heat release mode, the heat source **132** and the pump **133** are put into operation, and the mixing valve **135** is set so that part or all of the heating medium flows inside the heat storage device **12**. The heating medium is, for example, heated to an intermediate temperature between an outside air temperature and the freezing point of the latent heat storage material **111** by the heat source **132**, and then flows into the heat storage device **12**. This raises the temperature of the latent heat storage material **111**. At this point in time, the alternating-current voltage is being applied to the counter electrodes **113**. Therefore, even in a case where the latent heat storage material **111** is heated by the heating medium, the supercooled state of the latent heat storage material **111** is stably maintained. After elapse of a predetermined time from the start of the heating operation by the air heating device **13**, the alternating-current power source **114** stops application of the alternating-current voltage between the pair of counter electrodes **113**. This releases the supercooled state of the latent heat storage material **111**, and latent heat is released from the latent heat storage material **111**. The heating medium is heated by the heat released from the latent heat storage material **111**. The heating medium whose temperature has been raised heats air in the heat exchanger **131**. In a case where the temperature of the air heated in the heat exchanger **131** exceeds a necessary temperature, the mixing valve **135** may be controlled so that the amount of heating medium flowing inside the heat storage device **12** decreases and so that the amount of heating medium flowing in the bypass pipe **136** increases. This suppresses an increase in the temperature of the heating medium and reduces the temperature of the air. Conversely, in a case where the temperature of the air is below the necessary temperature, the mixing valve **135** may be controlled so that the amount of heating medium flowing inside the heat storage device **12** increases. At the start of activation of the air heating device **13**, there are cases in which the heat source **132** sometimes cannot instantly exert sufficient heating ability. In these cases, the heat storage device **12** of Embodiment 1 can compensate the insufficiency of the ability of the heat source **132** at the start of activation. The heat source **132** illustrated in FIG. **3** may be, for example, an engine of an automobile. In this case, for example, when the engine is put into operation again, application of the alternating-current voltage in the heat storage device **12** is stopped. This releases heat from the latent heat storage material **111**, and this heat warms the engine.

[0065] The supercooled state of the latent heat storage material **111** may be released just by stopping application of the alternating-current voltage between the counter electrodes **113**. However, in a case where the degree of supercooling of the latent heat storage material **111** is small, and the latent heat storage material **111** tends to remain in a supercooled state, the supercooling releasing means provided in the heat storage device **12** or the heat storage unit **11** may be also used.

Experiment 1

[0066] Experiment 1 using a test unit having a similar configuration to the heat storage unit **11** of Embodiment 1 is described below.

[0067] FIG. **7** illustrates a configuration of a test unit **71** used in Experiment 1. A container **712** was an acrylic container having an inner volume of 4 mL. A latent heat storage material **711** was a sodium acetate solution having a concentration of 55% by weight. A pair of counter electrodes **713** were stainless-steel counter electrodes disposed at an interval of 2 mm. The latent heat storage material **711** filled the container **712** and was in contact with the pair of counter electrodes **713**. A thermocouple **716** for detecting the temperature of the latent heat storage material **711** was inserted from a side surface of the container **712** and was in contact with the latent heat storage material **711**. Twenty test units **71** having this configuration were prepared, and an alternating-current power source was connected to the counter electrodes **713** of ten test units **71** out of these test units **71**. The alternating-current power source was not connected to the counter electrodes **713** of the remaining ten test units **71**.

[0068] The twenty test units **71** were once immersed in hot water of 80° C. After it was confirmed that the latent heat storage material **711** completely dissolved, these test units **71** were cooled by being put into a constant-temperature bath kept at −20° C. Here, an alternating-current voltage whose voltage peak value is 40 mV was continuously applied to the counter electrodes **713** of the ten test units **71** to which the alternating-current power source was connected. Application of the alternating-current voltage started at a point in time at which cooling of the test units **71** started.

[0069] The frequency of the alternating-current voltage applied to the counter electrodes **713** was set to 50 kHz, which is larger than 38 kHz that is the relaxation frequency fm ($r^*(\Delta T)$) of a critical nucleus at −20° C. Therefore, the frequency of the alternating-current voltage corresponds to a frequency that inhibits growth of a solid-phase particle which is contained in the latent heat storage material **711** and whose radius is smaller than a critical nucleus radius. Note that as a result of measuring dielectric relaxation of the sodium acetate solution at −20° C. to 0° C., a minimum value of the relaxation frequency corresponding to orientation relaxation was 70 kHz to 100 kHz.

[0070] In the twenty test units **71**, a time elapsed from a point in time at which the temperature of the latent heat storage material **711** reached −20° C. to a point in time at which a supercooled state was released by spontaneous nucleation was measured. This elapsed time corresponds to a time during which supercooling is maintained.

[0071] As a result of measurement, the ten test units **71** to which the alternating-current voltage was not applied escaped from the supercooled state within 18 hours due to spontaneous nucleation. The ten test units **71** to which the alternating-current voltage was applied maintained the supercooled state for 7 or more days. This experiment result shows that the heat storage device **12** of Embodiment 1 allows the latent heat storage material **111** to maintain a supercooled state. Note that when a voltage of 40 mV is applied between the pair of counter electrodes **713** disposed an interval of 2 mm, the intensity of an electric field between the pair of counter electrodes **713** is equivalent to 20 V/m. In view of dielectric loss, a larger electric field intensity may be applied between the counter electrodes **713**. An interval between the pair of counter electrodes **713** and a voltage applied between the counter electrodes **713** can be set as appropriate. In a case where the latent heat storage material contains sodium acetate hydrate and the counter electrodes **713** are in direct contact with the latent heat storage material **711**, the applied voltage is, for example, set to 1.2 V or lower. This makes it possible to prevent electrolysis of the latent heat storage material **711**.

Embodiment 2

[0072] In Embodiment 2, an example of a method for determining the magnitude of an alternating-current voltage applied to counter electrodes **113** is described. Configurations of heat storage units **11**, a heat storage device **12**, and an air heating device **13** are identical to those described in Embodiment 1. A method for driving the heat storage device **12** and the air heating device **13** is identical to that described in Embodiment 1 except for the magnitude (peak value) of the alternating-current voltage.

[Magnitude of Alternating-Current Voltage]

[0073] In a case where an external electric field E is being applied to a latent heat storage material **111**, a free energy difference ΔG (r) may be expressed by the following expression (4):

$$\Delta G(r) = G_\sigma \Delta S - G_L \Delta T \Delta V + G_E E^2 \Delta V \tag{4}$$

$$G_L = \frac{\Delta H\rho}{T_e},\ G_E = \frac{3\varepsilon_L(1-\varepsilon_S/\varepsilon_L)}{8\pi(2+\varepsilon_S/\varepsilon_L)}$$

[0074] where ΔS is surface area of a solid-phase particle, ΔV is a volume of the solid-phase particle, ΔT is the degree of supercooling, E is an external electric field, Gσ is a surface energy coefficient, GL is a volume energy coefficient per unit degree of supercooling, GE is an external electric field energy coefficient, ∈L is permittivity of a liquid phase of the latent heat storage material, and ∈S is permittivity of a solid phase of the latent heat storage material. The first term of the right side of expression (4) shows that as the surface area of the solid-phase particle increases, energy needed to form an interface increases. The second term of the right side shows that as the volume of the solid-phase particle increases, the free energy becomes stable due to cohesion. The third term of the right side shows that as the volume of the solid-phase particle increases, energy needed to counter a stress in the external electric field increases. The stress in the external electric field is as follows.

[0075] FIG. **8** illustrates a line of electric force obtained in a case where a solid-phase particle **52** is disposed in a liquid phase **51** and the external electric field E is applied therein. As illustrated in FIG. **8**, since permittivity ∈S of the solid-phase particle **52** is smaller than permittivity ∈L of the liquid phase **51**, the line of electric force is distorted. As a result, a stress towards the inside of the solid-phase particle **52** occurs on an interface between the solid-phase particle **52** and the liquid phase **51**. This stress prevents an increase in the volume of the solid-phase particle **52**, that is, prevents growth of the solid-phase particle **52**.

[0076] The second term of the right side of expression (4) contributes to lowering an energy barrier needed for the radius of the solid-phase particle to exceed a critical nucleus, and the third term of the right side contributes to heightening the energy barrier. Accordingly, for example, in a case where the latter exceeds the former, the supercooled state is more stably maintained. Therefore, in order to avoid spontaneous growth of the solid-phase particle, the magnitude (amplitude) of the alternating-current voltage may be, for example, set so as to exceed the electric field intensity Es described in the following expression (5):

$$E_s = \sqrt{\frac{G_L \Delta T}{G_E}} \tag{5}$$

[0077] FIG. **9** illustrates an example of a configuration of a heat storage unit. In FIG. **9**, each of the counter electrodes **113** includes a metal plate **31**, an insulation layer **32** that coats a first main surface of the metal plate **31**, and an insulation layer **32** that coats a second main surface of the metal plate **31**. In a case where the counter electrodes **113** have the insulation layer **32** at least on a surface that is in contact with the latent heat storage material **111**, almost no electric current flows to the latent heat storage material **111**. This can prevent deformation of the latent heat storage material **111** and save electric power. In the heat storage unit illustrated in FIG. **9**, for example, an alternating-current voltage having an amplitude V that satisfies the following expression (6) may be applied between the counter electrodes **113**:

$$V = \frac{2\varepsilon_L d_2 + \varepsilon_i d_1}{\varepsilon_i d_1} E_s(2d_{edl}) \tag{6}$$

[0078] where d**1** is the thickness of the latent heat storage material **111**, d**2** is the thickness of the insulation layer **32**, ∈i is permittivity of the insulation layer **32**, and dedl is the thickness of an electric double layer formed on an interface between the latent heat storage material **111** and the insulation layer **32**. Note that in a case where an electric double layer is not formed on the latent heat storage material **111**, and a uniform electric field is generated over a thickness direction of the latent heat storage material **111**, **2***dedl* may be d**1**.

[0079] According to expressions (4) to (6), in a case where sodium acetate trihydrate is maintained in a supercooled state at an outside air temperature of −23° C., a voltage peak value V of the alternating-current voltage is, for example, 2.58 V. Note that in calculation of expressions (4) and (5), the permittivity ∈L of the liquid phase is set to 2.74×10^{-9} F/m, the permittivity ∈S of the solid phase is set to 5.49×10^{-10} F/m (at 50 kHz), and the other physical property values are set by referring to CRIEPI Research Report mentioned above. In calculation of expression (6), polyethylene terephthalate is used as the insulation layer, permittivity ∈i of the insulation layer is set to 2.66×10^{-11} F/m, and the film thickness d**2** of the insulation layer is set to 1.2×10^{-5} m. The thickness d**1** of the latent heat storage material is set to 4.0×10^{-3} m, and the thickness dedl of the electric double layer is set to 1.0×10^{-9} m.

[0080] Note that the voltage peak value of the alternating-current voltage is not limited to that mentioned above. A method for determining the voltage peak value of the alternating-current voltage is not limited to that mentioned above. The voltage peak value of the alternating-current voltage in the present disclosure is not limited to a specific one, provided that the supercooled state of the latent heat storage material can be maintained, and a method for determining the voltage peak value of the alternating-current voltage is not limited to a specific one. The voltage peak value may be determined by using another theoretical formula or may be determined by using an experimental formula. The voltage peak value may be determined without using any formula, and may be determined by using a table in which predetermined parameters and associated voltage peak values are listed. The voltage peak value can be determined by using an empirical method or a semi-empirical method.

[0081] The alternating-current voltage may be, for example, applied to a heat storage unit that includes an electrode having no insulation layer. Meanwhile, in a case where the electrode has insulation layer, dielectric polarization can be generated while preventing occurrence of electrochemical reaction of the latent heat storage material. This makes it possible to efficiently maintain the supercooled state of the latent heat storage material.

Experiment 2

[0082] An experiment using test units having a similar configuration to the heat storage units **11** of Embodiment 2 is described below.

[0083] The test units used in Experiment 2 had an overall configuration illustrated in FIG. **7**, and counter electrodes of the test units were insulating electrodes as illustrated in FIG. **9**. A container **712** was an acrylic container having an inner volume of 4 mL. A latent heat storage material **711** was a sodium acetate solution having a concentration of 55% by weight. A stainless plate was coated with polyethylene terephthalate coating (thickness: 12 μm) to obtain a pair of insulating electrodes. The pair of insulating electrodes were disposed at an interval of 4 mm so as to be in contact with a latent heat storage material. A thermocouple for detecting the temperature of the latent heat storage material was inserted from a side surface of the container and was in contact with the latent heat storage material. Sixteen test units having this configuration were prepared. These test units were evaluated as follows under Condition A in which an alternating-current voltage is applied to the insulating electrodes and Condition B in which the alternating-current voltage is not applied to the insulating electrodes.

[0084] The sixteen test units were once immersed in hot water of 80° C. After it was confirmed that the latent heat storage material completely dissolved, these test units were cooled by being put into a constant-temperature bath kept at −23° C. In Condition A, a predetermined alternating-current voltage was continuously applied to the insulating electrodes of the test units. At this point, a voltage peak value V of the alternating-current voltage was 2.58 V. In Condition B, no alternating-current voltage was applied to the insulating electrodes of the test units.

[0085] A time elapsed from a point in time at which the temperature of the latent heat storage material reached −23° C. to a point in time at which the supercooled state was released due to spontaneous nucleation was measured. This elapsed time corresponds to a time during which supercooling is maintained.

[0086] In the measurement under Condition B, supercooling was maintained for 12 hours in approximately 10% of the test units. Meanwhile, in the measurement under Condition A, supercooling was maintained for 12 hours in approximately 60% of the test units. In the measurement under Condition B, supercooling was not maintained for 4 hours in approximately 70% of the test units. In the measurement under Condition A, supercooling was not maintained for 4 hours in approximately 30% of the test units. This result shows that the supercooled state of the latent heat storage material can be stably maintained by applying an appropriate alternating-current voltage.

Experiment 3

[0087] The following experiment was conducted in order to confirm an effect of an insulation layer of electrodes.

[0088] Both of two test units used in Experiment 3 have an overall configuration as illustrated in FIG. **7**. One of the two test units includes insulating electrodes as illustrated in FIG. **9**, and the other one of the two test units includes electrodes (stainless plates) having no insulation layer. The thickness of the insulation layer was 12 μm. In each of the test units, the pair of electrodes were disposed at an interval of 4 mm. The configuration of each of the test units is similar to that of Experiment 2 except for this. In each of the test units, impedance between the electrodes was measured.

[0089] As a result, the impedance of the test unit that includes the electrodes having no insulation layer was 1.5 kΩ. The impedance of the test unit that includes the insulating electrodes was 700 M. Accordingly, when an applied voltage was 2.58 V, for example, consumed electric power of the former test unit was 4.4 mW, and consumed electric power of the latter test unit was 9.5 nW. That is, in a case where electrodes of a heat storage unit have an insulation layer, consumed electric power can be markedly reduced.

[0090] The thickness of the insulation layer and the interval between the pair of insulating electrodes are not limited to the above values. In consideration of heat-transfer performance of the heat storage unit and an applied voltage, the thickness of insulation layer may be, for example, in a range of 10 μm to 100 μm. The interval between the insulating electrodes may be, for example, in a range of 1 mm to 10 mm. The voltage V of the alternating-current voltage applied to the insulating electrodes may be, for example, determined on the basis of the calculation method described above. For example, in a case where the thickness of the insulation layer is 10 μm and the interval between the insulating electrodes is 10 mm, the applied voltage may be set to 2 V. For example, in a case where the thickness of the insulation layer is 100 μm and the interval between the insulating electrodes is 1 mm, the applied voltage may be set to 35 V. A peak value of the alternating-current voltage may be, for example, in a range of 2V to 35V. By applying an alternating-current voltage having an appropriate value to the electrodes, the supercooled state of the latent heat storage material can be maintained, and furthermore electrolysis of the latent heat storage material can be prevented.

Embodiment 3

[0091] FIG. **10** illustrates a configuration of a heat storage unit **11'** according to Embodiment 3. Elements in Embodiment 3 that are identical to those in Embodiment 1 or 2 are given identical reference numerals, and therefore may not be explained repeatedly. The description in each of the embodiments can be applied to another embodiment unless they are technically inconsistent.

[0092] The heat storage unit **11'** includes a temperature sensor **116** that directly or indirectly detects the temperature of a latent heat storage material **111**. A controller **115** determines at least one of the frequency and voltage peak value of an alternating-current voltage applied to counter electrodes **113** on the basis of the temperature detected by the temperature sensor **116**. For example, the controller **115** may calculate, on the basis of the temperature, a relaxation frequency that corresponds to a critical nucleus and/or a relaxation frequency that corresponds to a solid-phase particle included in the latent heat storage material, whose radius is smaller than that of a critical nucleus. For example, the controller **115** may calculate a voltage peak value that suppresses growth of the solid-phase particle on the basis of the result of detection by the temperature sensor **116**. In Embodiment 3, the alternating-current power source **114** is a variable frequency power source or a variable voltage power source. At least one of the frequency and voltage peak value of the alternating-current voltage is changed in accordance with the result of detection by the temperature sensor **116**. According to this method, an optimum alternating-current voltage can be applied to the counter electrodes **113** in accordance with the temperature of the latent heat storage material **111**. As a result, the supercooled state of the latent heat storage material **111** can be more stably maintained.

[0093] In a case where a heat storage device **12** includes a plurality of heat storage units **11'**, there is a possibility that the temperature of the latent heat storage material **111** is different among the heat storage units **11'**. In this case, alternating-current voltages of different frequencies and/or different voltage peak values may be applied to the counter electrodes **113** of the heat storage units **11'**. Alternatively, at least one of the frequency and voltage peak value of the alternating-current voltage may be determined on the basis of a minimum temperature out of a plurality of temperatures exhibited by the plurality of heat storage units **11'**.

[0094] The temperature sensor **116** may be provided in at least one of the heat storage units **11'** of the heat storage device **12**. For example, in a case where a heat storage unit **11'** that exhibits a minimum temperature has been specified in advance, the temperature sensor **116** may be provided in this heat storage unit **11'** only. The position in the heat storage unit **11'** at which the temperature sensor **116** is attached is not limited to a position that is in direct contact with the latent heat storage material **111** as illustrated in FIG. **10**. For example, the temperature sensor **116** may be provided inside a container **112** or on an external surface of the container **112**. In this case, the temperature of the latent heat storage material **111** may be estimated from the temperature detected by the temperature sensor **116**. For example, a relationship between a value detected by the temperature sensor **116** and an actual temperature of the latent heat storage material **111** may be examined in advance. The controller **115** may have a table in which a relationship between a value detected by the temperature sensor **116** and an actual temperature of the latent heat storage material **111** is described.

[Driving Method]

[0095] An example of a method for driving an air heating device that includes the heat storage device **12** of Embodiment 3 is described below. The air heating device **13** and/or the heat storage device **12** operates in any one of a plurality of modes including a heat storage mode, a heat retention mode, and a heat release mode. Common points of the driving method of Embodiment 3 with the driving method of Embodiment 1 are not repeatedly explained.

[0096] A heat storage mode of the air heating device **13** is similar to that of Embodiment 1. Whether or not all of the latent heat storage material **111** has dissolved may be determined on the basis of a value detected by the temperature sensor **116**.

[0097] A heat retention mode of the air heating device **13** is similar to that of Embodiment 1. A timing at which the alternating-current voltage is applied to the pair of counter electrodes **113** may be determined on the basis of the value detected by the temperature sensor **116**. For example, the alternating-current voltage may be applied between the counter electrodes when it is determined that the temperature of the latent heat storage material **111** becomes lower than the freezing point of the latent heat storage material **111**.

[0098] In the heat retention mode, for example, the controller **115** may determine the frequency of the alternating-current voltage on the basis of the value detected by the temperature sensor **116** and expressions (1) and (2) mentioned above. In the heat retention mode, for example, the controller **115** may determine the voltage peak value of the alternating-current voltage on the basis of the value detected by the temperature sensor **116** and expressions (4) and (5) mentioned above. Note that the degree of supercooling ΔT may be a value obtained by subtracting the temperature T of the latent heat storage material detected by the temperature sensor **116** from the freezing point Te of the latent heat storage material **111**.

[0099] Alternatively, in the heat retention mode, the controller **115** may determine the frequency of the alternating-current voltage on the basis of a table in which a relationship between the value detected by the temperature sensor and a relaxation frequency is described. In the heat retention mode, the controller **115** may determine the voltage peak value of the alternating-current voltage on the basis of a table in which a relationship between the value detected by the temperature sensor and the voltage peak value is described. These tables are, for example, prepared in advance by using an empirical method or a semi-empirical method. In preparing the tables, the various calculation in Embodiments 1 and 2 may be used.

[0100] According to Embodiment 3, the alternating-current voltage for maintaining a supercooled state is determined on the basis of the storage temperature of the latent heat storage material **111**. Therefore, the heat storage device **12** according to Embodiment 3 can stably maintain the supercooled state of the latent heat storage material **111** irrespective of the temperature change.

Embodiment 4

[0101] FIG. **11** illustrates an example of a configuration of a heat storage unit **91** according to Embodiment 4. The heat storage unit **91** includes a container **912** and a latent heat storage material **111** contained in the container **912**. The container **912** is made up of a plurality of laminate films **913** (e.g. a pair of laminate films **913**). Each of the laminate films **913** has a flexible metal foil **931** and an insulation layer **932** that coats a surface of the metal foil **931**. In this case, the metal foil **931** functions as an electrically conductive electrode main body. The metal foil **931** is, for example, sandwiched between the insulation layers **932**. The latent heat storage material **111** is not in contact with the metal foil **931**.

[0102] In Embodiment 4, the laminate films **913** that constitute the container **912** are used as insulating electrodes. The metal foil **931** is electrically connected to the alternating-current power source **114**. This allows an alternating-current electric field to be applied to the latent heat storage material **111**. An interface between the latent heat storage material **111** and the laminate films **913** defines the latent heat storage material **111**. Accordingly, in a case where the latent heat storage material **111** in a liquid phase is an electrolyte solution, an electric double layer is formed, by voltage application, on an entire surface along which the latent heat storage material **111** and the container **912** are in contact with each other. This allows an electric field of a sufficient intensity to be applied to the latent heat storage material **111**.

[0103] For example, the latent heat storage material **111** has a maximum thickness dmax at a central part of the container **912** and has a minimum thickness dmin in the vicinity of a peripheral portion of the container **912** where the laminate films **913** are bonded. In a case where a voltage peak value V of the alternating-current voltage is calculated by using expression (6) mentioned above, the thickness d1 of the latent heat storage material may be the minimum thickness dmin of the latent heat storage material **111**.

[0104] In each of the embodiments, a method for maintaining a liquid phase in a case where a latent heat storage material in a liquid phase is cooled below a freezing point has been described. However, each of the embodiments may be applied to other phase transition phenomena. For example, each of the embodiments may be applied as a method for maintaining one of gas and liquid phases above an equilibrium temperature in gas-liquid phase transition. That is, "supercooled state" in the present disclosure encompasses a metastable state in gas-liquid phase transition.

[0105] The heat storage device described in the present disclosure may be, for example, applied to a heat source for warming such as an internal-combustion engine of an automobile, a transmission, or a rechargeable battery.

[0106] While the present disclosure has been described with respect to exemplary embodiments thereof, it will be apparent to those skilled in the art that the disclosure may be modified in numerous ways and may assume many embodiments other than those specifically described above. Accordingly, it is intended by the appended claims to cover all modifications of the disclosure that fall within the true spirit and scope of the disclosure.

What is claimed is:

1. A heat storage device comprising:

a pair of electrodes;

an alternating-current power source that applies an alternating-current voltage to the pair of electrodes; and

a latent heat storage material that is disposed between the pair of electrodes, the latent heat storage material being maintained in a supercooled state by the alternating-current voltage.

2. The heat storage device according to claim **1**, wherein each of the pair of electrodes includes an electrode main body having electrical conductivity and an insulation layer coating a surface of the electrode main body.

3. The heat storage device according to claim **2**, wherein the alternating-current voltage is in a range of 2 V to 35 V.

4. The heat storage device according to claim **1**, wherein a frequency of the alternating-current voltage is in a range of 10 kHz to 100 kHz.

5. The heat storage device according to claim **1**, wherein the alternating-current power source applies the alternating-current voltage to the pair of electrodes to maintain the supercooled state of the latent heat storage material, and then further stops application of the alternating-current voltage to release the supercooled state of the latent heat storage material.

6. The heat storage device according to claim **1**, further comprising a temperature sensor that directly or indirectly detects a temperature of the latent heat storage material, wherein

the alternating-current power source includes a variable frequency power source, and

a frequency of the alternating-current voltage is changed in accordance with the detected temperature.

7. The heat storage device according to claim **1**, further comprising a temperature sensor that directly or indirectly detects a temperature of the latent heat storage material, wherein

the alternating-current power source includes a variable voltage power source, and

the alternating-current voltage is changed in accordance with the detected temperature.

8. The heat storage device according to claim **1**, further comprising a temperature sensor that directly or indirectly detects a temperature of the latent heat storage material, wherein

the alternating-current power source selects whether or not the alternating-current voltage is applied to the pair of electrodes in accordance with the detected temperature.

9. The heat storage device according to claim **8**, wherein in a case where the temperature of the latent heat storage material is higher than a freezing point of the latent heat storage material, the alternating-current power source does not apply the alternating-current voltage to the pair of electrodes, and in a case where the temperature of the latent heat storage material is equal to or lower than the freezing point of the latent heat storage material, the alternating-current power source applies the alternating-current voltage to the pair of electrodes.

10. The heat storage device according to claim **1**, wherein after heat is applied to the latent heat storage material from outside of the heat storage device, the alternating-current power source applies the alternating-current voltage to the pair of electrodes to maintain the supercooled state of the latent heat storage material.

11. The heat storage device according to claim **1**, wherein the latent heat storage material contains a hydrated salt or sugar alcohol.

12. The heat storage device according to claim **1**, wherein the latent heat storage material is sodium acetate trihydrate.

13. A method of using a latent heat storage material, comprising:

applying heat to a latent heat storage material disposed between a pair of electrodes to melt the latent heat storage material;

after the melted latent heat storage material enters a supercooled state, applying an alternating-current voltage to the pair of electrodes to maintain the supercooled state of the latent heat storage material while the latent heat storage material retains the heat; and

stopping application of the alternating-current voltage to release the supercooled state of the latent heat storage material, allowing the heat to be released from the latent heat storage material.

* * * * *