



(12) **EUROPEAN PATENT APPLICATION**

(43) Date of publication:
26.06.2013 Bulletin 2013/26

(51) Int Cl.:
H05B 3/14 (2006.01)

(21) Application number: **12199164.0**

(22) Date of filing: **21.12.2012**

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA ME

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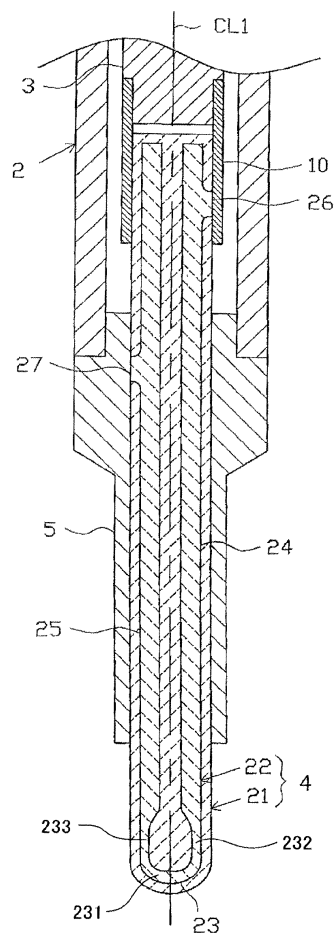
(30) Priority: **21.12.2011 JP 2011279122**
17.09.2012 JP 2012203784

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(54) **Ceramic heater and manufacturing method therefor, and heating apparatus**

(57) A ceramic heater having a substrate and a heat-generating element. The substrate is formed from an electrically insulating ceramic and extends rearward from the forward end of the ceramic heater in the direction of the axis. The heat-generating element has a heat-generating portion formed from an electrically conductive ceramic which contains silicon nitride and an electrically conductive material, disposed in a forward end portion of the substrate, and having a shape resembling the letter U as viewed along the direction of the axis. The heat-generating portion has a fracture toughness of $4.3 \text{ Mpa} \cdot \text{m}^{0.5}$ or more.

FIG. 3



Description**Field of the Invention**

5 **[0001]** The present invention relates to a ceramic heater in which a heat-generating element is held in a substrate, to a method of manufacturing the ceramic heater, and to a heating apparatus having the ceramic heater.

Background of the Invention

10 **[0002]** Conventionally, a glow plug used, for example, to help startup of a diesel engine includes a tubular metallic shell and a heater having an incorporated heat-generating element which generates heat through energization. The heater may be a ceramic heater. The ceramic heater is configured such that a heat-generating element made of electrically conductive ceramic is held in a substrate made of an electrically insulating ceramic (refer to, for example, Japanese Patent Application Laid-Open (*kokai*) No. 2006-351446).

15 **[0003]** Meanwhile, in view of a desire to reduce emissions, preferably, the interior of a combustion chamber is quickly raised to a high temperature. Thus, a recently proposed ceramic heater employs a heat-generating element formed from a material which contains, for example, a silicide or a carbide of molybdenum or tungsten as a main component so as to improve heat resistance of the heat-generating element, whereby, even when quick temperature rise (e.g., the temperature of the surface of the substrate is raised to 1,000°C or higher within two seconds) is repeated within a combustion chamber, the heat-generating element is unlikely to suffer an electrical disconnection (refer to, for example, Japanese Patent Application Laid-Open (*kokai*) No. 2010-181125).

Summary of the Invention

25 **[0004]** However, in recent years, in order to more effectively reduce emissions, there is a demand for far more quickly raising the temperature within a combustion chamber (e.g., ultrahigh-speed temperature raising to raise the temperature of the surface of the substrate to 1,000°C or higher within one second). When the conventional ceramic heater is energized for heating under the condition of ultrahigh-speed temperature raising, even though the heat-generating element has good heat resistance, the heat-generating element may suffer electrical disconnection at a relatively early stage. In this regard, the inventors of the present invention carried out extensive studies and found the following: conventionally, durability of the heat-generating element in terms of electrical disconnection (service life of the heat-generating element) is determined mainly from heat resistance; however, repeated application of a large thermal stress to the heat-generating element is responsible for the occurrence of an electrical disconnection in the heat-generating element.

30 **[0005]** The present invention has been conceived in view of the above circumstances. The present invention provides a ceramic heater which can exhibit effective restraint of the occurrence of an electrical disconnection in a heat-generating element even upon energization for heating under the condition of ultrahigh-speed temperature raising, thereby providing long service life.

[0006] Another aspect of the present invention is a method of manufacturing a ceramic heater as described above.

[0007] A still further aspect of the present invention is a heating apparatus having a ceramic heater as described above.

40 **[0008]** Configurations suitable for achieving the above aspects of the present invention will next be described in itemized form. When needed, actions and effects peculiar to the configurations will be described additionally.

[0009] Configuration 1.

[0010] In accordance with a first embodiment of the present invention, there is provided a ceramic heater of the present configuration that comprises a substrate and a heat-generating element. The substrate is formed from an electrically insulating ceramic and extends rearward from the forward end of the ceramic heater in the direction of an axis. The heat-generating element has a heat-generating portion formed from an electrically conductive ceramic which contains silicon nitride and an electrically conductive material, disposed in a forward end portion of the substrate, and having a shape resembling a letter U as viewed along the direction of the axis. The heat-generating portion has a fracture toughness of 4.3 MPa·m^{0.5} or more.

50 **[0011]** According to the above configuration 1, the heat-generating portion of the heat-generating element, the portion having a high temperature upon energization, has a fracture toughness of 4.3 MPa·m^{0.5} or more. By virtue of this, the heat-generating portion disposed in a forward end portion of the substrate has such a high strength as to resist, over a long period of time, a very large thermal stress which is repeatedly applied thereto. As a result, even upon energization for heating under the condition of ultrahigh-speed temperature raising, the occurrence of an electrical disconnection in the heat-generating element (heat-generating portion) can be effectively restrained, whereby the ceramic heater can provide long service life.

[0012] Configuration 2.

[0013] In accordance with a second embodiment of the present invention, there is provided a ceramic heater as

described in the above configuration 1, wherein the heat-generating element has electrically conductive lead portions connected to respective ends of the heat-generating portion located on the rear end side of the heat-generating portion, and the thickness of the heat-generating portion is 30% or less that of the lead portions.

[0014] According to the above configuration 2, the thickness of the heat-generating portion is 30% or less than that of the lead portions (corresponding to power supply paths to the heat-generating portion). Therefore, the cross-sectional area of the heat-generating portion can be greatly smaller than that of the lead portions, and thus, the electrical resistivity of the heat-generating portion can be far more higher than that of the lead portions. As a result, at the time of energization, the temperature of the heat-generating portion can be raised quite quickly without being influenced by the lead portions, so that ultrahigh-speed temperature raising (the temperature of the surface of the substrate is raised to 1,000°C or higher within one second) can be implemented relatively easily.

[0015] Meanwhile, the above configuration 2 involves concern about the occurrence of an electrical disconnection in the heat-generating element (heat-generating portion) at the time of ultrahigh-speed temperature raising, since the heat-generating portion is considerably thin as compared with the lead portions. However, the concern can be eradicated through employment of the above configuration 1. In other words, the above configuration 1 is particularly significant for a ceramic heater which has the heat-generating portion having a thickness of 30% or less that of the lead portions and thus involves much concern about the occurrence of an electrical disconnection in the heat-generating portion.

[0016] In employment of the above configuration 2, different materials may be used to form the heat-generating portion and the lead portions, or the heat-generating portion and the lead portions may be formed from the same material. When different materials are to be used to form the heat-generating portion and the lead portions, a material used to form the lead portions may be a metal material or an electrically conductive ceramic. However, in the case where different materials are used to form the heat-generating portion and the lead portions, in association with the difference in material, damage, such as cracking, may arise to a certain extent at the joints between the heat-generating portion and the lead portions.

[0017] Configuration 3.

[0018] In accordance with a third embodiment of the present invention, there is provided a ceramic heater as described in configuration 2 which is configured such that the heat-generating portion and the lead portions are formed from the same material. Employment of the present configuration can prevent the occurrence of damage, such as cracking, at the joints between the heat-generating portion and the lead portions and can improve productivity because of use of the same material.

[0019] Configuration 4.

[0020] In accordance with a fourth embodiment of the present invention, there is provided a heating apparatus according to any one of the above configurations 1 to 3, having an energization control unit configured to adjust supply power to the heat-generating element, and adapted to control heat generation of the heat-generating portion through adjustment of the supply power. The energization control unit supplies power to the heat-generating element in such a manner as to raise the surface temperature of a heating portion of the substrate corresponding to the heat-generating portion from room temperature to 1,000°C within one second.

[0021] In a heating apparatus, such as that of the above configuration 4, in which the energization control unit supplies power to the heat-generating element in such a manner as to raise the surface temperature of a heating portion of the substrate located around the heat-generating portion from room temperature to 1,000°C within one second; i.e., in a heating apparatus in which the heat-generating element executes ultrahigh-speed temperature raising, an electrical disconnection is more likely to occur in the heat-generating element (heat-generating portion). However, through employment of the ceramic heater of the above configuration 1, etc., the occurrence of an electrical disconnection in the heat-generating element can be more reliably prevented. In other words, the ceramic heater of the above configuration 1, etc., fully exhibits its superior durability against ultrahigh-speed temperature raising when used in a heating apparatus in which power is supplied to the heat-generating element in such a manner as to raise the surface temperature of a heating portion of the substrate from room temperature to 1,000°C within one second.

[0022] Configuration 5.

[0023] In accordance with a fifth embodiment of the present invention, there is provided a method of manufacturing a ceramic heater which comprises a substrate formed from an electrically insulating ceramic and extending rearward from the forward end of the ceramic heater in the direction of an axis, and a heat-generating element having a heat-generating portion containing silicon nitride and an electrically conductive material, disposed in a forward end portion of the substrate, and having a shape resembling a letter U as viewed along the direction of the axis. The method comprises: a green element forming step of forming a green element body which is to become the heat-generating element, from an element material which contains an electrically conductive material powder and silicon nitride; a holding body forming step of forming a holding body in which the green element body is embedded in a green insulation body which is formed from a substrate material containing an electrically insulating ceramic powder and which is to become the substrate; a debinding step of debinding the holding body; and a firing step of firing, after the debinding step, the holding body under pressure. The green element body has a prospective heat-generating portion which is to become the heat-generating portion. As measured after the debinding step and before the firing step, a portion of the green insulation

body located around the prospective heat-generating portion has a relative density of 46.3% or more.

[0024] As used herein, the term "relative density" means a proportion of the density of the green insulation body located around the prospective heat-generating portion expressed as a percent of the theoretical density of the substrate material as measured after the debinding step and before the firing step.

[0025] According to the above configuration 5, as measured after the debinding step and before the firing step, a portion of the green insulation body located around the prospective heat-generating portion has a relative density of 46.3% or more. Therefore, in the firing step, a large pressure can be applied from the green insulation body to the prospective heat-generating portion, whereby there can be accelerated the grain growth of silicon nitride which constitutes the green element body. As a result, the fracture toughness of the heat-generating portion can be more reliably increased, so that the ceramic heater having superior durability against ultrahigh-speed temperature raising can be more reliably manufactured.

[0026] Configuration 6.

[0027] In accordance with a sixth embodiment of the present invention, there is provided a method of manufacturing a ceramic heater as described above, in the above configuration 5, wherein the ceramic heater is such that power is supplied to the heat-generating element in such a manner as to raise the surface temperature of a heating portion of the substrate corresponding to the heat-generating portion from room temperature to 1,000°C within one second.

[0028] As in the case of the above configuration 6, in the case where power is supplied to the heat-generating element in such a manner as to raise the surface temperature of a heating portion of the substrate corresponding to the heat-generating portion from room temperature to 1,000°C within one second; i.e., in the case where the heat-generating element executes ultrahigh-speed temperature raising, an electrical disconnection is more likely to occur in the heat-generating element (heat-generating portion). However, even in such a case, by use of the ceramic heater manufactured by the method of the above configuration 4; i.e., by use of the ceramic heater manufactured such that the heat-generating portion has sufficiently high fracture toughness, the occurrence of an electrical disconnection in the heat-generating element can be more reliably prevented. In other words, the above configuration 5 is particularly significant in manufacture of the ceramic heater in which power is supplied to the heat-generating element in such a manner as to raise the surface temperature of a heating portion of the substrate from room temperature to 1,000°C within one second.

Brief Description of the Drawings

[0029] FIG. 1 is a block diagram showing the schematic configuration of a heating apparatus.

[0030] FIG. 2A is a sectional view of a glow plug.

[0031] FIG. 2B is a front view of the glow plug.

[0032] FIG. 3 is a fragmentary, enlarged, sectional view showing the configuration of a ceramic heater.

[0033] FIG. 4 is a side view showing the configuration of a heat-generating element.

[0034] FIG. 5 is a flowchart showing a process of manufacturing the ceramic heater.

[0035] FIG. 6 is a perspective view showing a step of placing a green element body in an accommodation cavity of a halved green insulation body.

[0036] FIGS. 7A and 7B are sectional views showing a mold, etc., to be used in a green element body forming step, wherein FIG. 7A is a sectional plan view, and FIG. 7B is a sectional side view.

[0037] FIG. 8 is a perspective view showing a mold and an outer frame to be used in a halved green insulation body forming step.

[0038] FIG. 9 is a perspective view showing the configuration of an upper mold to be used in the halved green insulation body forming step.

[0039] FIG. 10 is a sectional view showing an operation of pressing a substrate material by use of the mold and the outer frame in the halved green insulation body forming step.

[0040] FIG. 11 is a perspective view showing the configuration of a holding body.

[0041] FIG. 12 is a perspective view showing a mold and an outer frame to be used in a holding body forming step.

[0042] FIG. 13 is a sectional view showing an operation of pressing the substrate material by use of a mold and an outer frame in the holding body forming step.

[0043] FIG. 14A is a sectional view showing the direction of pressing in firing the holding body.

[0044] FIG. 14B is a sectional view showing a fired body yielded by firing the holding body.

[0045] FIG. 15 is a sectional view of a green element body for explaining a region whose relative density is to be measured.

[0046] FIG. 16 is a sectional view showing a mold, etc., to be used in the holding body forming step in another embodiment.

[0047] FIG. 17 is a schematic explanatory view showing a position to drive a diamond indenter on the surface-to-be-measured of a heat-generating portion of the heat-generating element, for calculating the fracture toughness of the heat-generating portion.

Brief Description of Preferred Embodiments

[0048] An embodiment of the present invention will next be described with reference to the drawings. FIG. 1 is a block diagram showing the schematic configuration of a heating apparatus 101.

[0049] The heating apparatus 101 includes a ceramic glow plug 1 (hereinafter, referred to as the "glow plug 1") having a ceramic heater 4, and a glow control unit (GCU) 102 (an energization control unit) to control energization of the glow plug 1. FIG. 1 shows only a single glow plug 1. However, an actual engine has a plurality of cylinders, and the glow plug 1 and a switch 104, which will be described later, are provided for each of the cylinders.

[0050] The GCU 102 operates by power supplied from a battery VA and includes a microcomputer 103 having a CPU, a ROM, a RAM, etc., and the switch 104 adapted to turn ON/OFF the supply of power to the glow plug 1 from the battery VA.

[0051] The GCU 102 controls energization of the glow plug 1 under PWM control such that the switch 104 turns ON/OFF the supply of power to the glow plug 1 under instructions from the microcomputer 103.

[0052] In the present embodiment, in order to measure the resistance of the glow plug 1, the switch 104 is configured such that an FET (field effect transistor) having a current detecting function is operated via an NPN transistor, etc. Additionally, the microcomputer 103 is connected to the power supply terminals of the glow plug 1 via a voltage-dividing resistor (not shown), and a voltage obtained by dividing a voltage to be applied to the glow plug 1 (a voltage output from the GCU 102) is input to the microcomputer 103. The microcomputer 103 can calculate an applied voltage to the glow plug 1 on the basis of the input voltage and can measure the resistance of the glow plug 1 from the applied voltage and current which flows through the glow plug 1 and is measured by the switch 104.

[0053] Additionally, in the present embodiment, the microcomputer 103 is designed to perform, when the engine key is turned ON, preglow energization for quickly raising the temperature of the glow plug 1 (the ceramic heater 4), and thereafter, after-glow energization for maintaining the glow plug 1 at a predetermined temperature for a predetermined period of time.

[0054] In the present embodiment, in preglow energization, power is supplied to the glow plug 1 in such a manner as to raise the temperature of the surface of a substrate 21, which will be described later, of the glow plug 1 from room temperature to 1,000°C within one second (ultrahigh-speed temperature raising).

[0055] In preglow energization, the temperature of the glow plug 1 is quickly raised to a target temperature irrespective of characteristics of the glow plug 1, by matching, with a predetermined reference curve, a curve indicative of the relationship between power to be supplied to the glow plug 1 and elapsed time. Specifically, by use of a relational expression or a table indicative of the predetermined reference curve, power to be supplied at a point of elapsed time from start of energization is obtained. From the relationship between current flowing through the glow plug 1 and power to be supplied at a point of elapsed time, voltage to be applied to the glow plug 1 is obtained, and voltage to be applied to the glow plug 1 (effective voltage) is controlled under PWM control. By this procedure, power is supplied such that the relational curve coincides with the reference curve, whereby the glow plug 1 (the ceramic heater 4) generates heat according to cumulative power having been supplied until a certain point of elapsed time in the temperature raising process. Therefore, upon completion of the supply of power according to the reference curve, the glow plug 1 reaches a target temperature in time of the reference curve.

[0056] In after-glow energization, supply power to the glow plug 1 is adjusted such that the surface temperature of the substrate 21 is maintained at a high temperature (e.g., 1,200°C or higher) for a relatively long period of time (e.g., about 180 seconds).

[0057] Next, the glow plug 1 having the ceramic heater 4 will be described with reference to FIGS. 2A and 2B, FIG. 3, etc. FIG. 2A is a sectional view of the glow plug 1, and FIG. 2B is a front view of the glow plug 1. FIG. 3 is a fragmentary, enlarged, sectional view of the glow plug 1, primarily showing the ceramic heater 4. In description with reference to FIGS. 2A, 2B, and 3, the lower side of the glow plug 1 (the ceramic heater 4) is referred to as the forward side of the glow plug 1, and the upper side as the rear side of the glow plug 1.

[0058] As shown in FIGS. 2A and 2B, the glow plug 1 includes a housing 2, an axial rod 3, the ceramic heater 4, a sleeve 5, and a terminal pin 6 or a like.

[0059] The housing 2 is formed from a predetermined metal material (e.g., an iron-based material, such as S45C) and has an axial bore 7 extending along the direction of an axis CL1. Furthermore, as viewed externally, the housing 2 has an externally threaded portion 8 formed at its central portion with respect to the direction of the axis CL1. The externally threaded portion 8 is adapted to mount the glow plug 1 to, for example, the cylinder head of an engine. Also, as viewed externally, the housing 2 has a flange-like tool engagement portion 9 formed at its circumference of the rear end portion and having a hexagonal cross section. When the glow plug 1 (the externally threaded portion 8) is to be mounted to, for example, the cylinder head, a mounting tool is engaged with the tool engagement portion 9.

[0060] The axial bore 7 of the housing 2 accommodates the axial rod 3 made of metal and having a circular cross section. A forward end portion of the axial rod 3 is press-fitted into a rear end portion of a cylindrical connection member 10 formed from a metal material (e.g., an iron-based material, such as SUS). A rear end portion of the ceramic heater 4 is press-fitted into a forward end portion of the connection member 10. Thus, the axial rod 3 and the ceramic heater

4 are mechanically and electrically connected to each other via the connection member 10. Additionally, the axial rod 3 has a diameter-reduced portion 13 formed at its intermediate portion that is smaller in outside diameter than its forward and rear end portions. The diameter-reduced portion 13 mitigates stress transmitted to the axial rod 3. Notably, in place of the connection member 10, predetermined lead wires or the like may be used to electrically connect the axial rod 3 and the ceramic heater 4 to each other.

[0061] Furthermore, a terminal pin 6 made of metal is fixedly crimped to a rear end portion of the axial rod 3. An electrically insulating bushing 11, formed from an electrically insulating material, is disposed between a forward end portion of the terminal pin 6 and a rear end portion of the housing 2 in order to prevent direct electrical communication (short circuit) therebetween. Additionally, an O-ring 12 formed from an electrically insulating material is provided between the housing 2 and the axial rod 3 in such a manner as to be in contact with a forward end portion of the electrically insulating bushing 11 in order to improve gastightness or a like within the axial bore 7.

[0062] Meanwhile, the sleeve 5 is formed into a cylindrical shape from a predetermined metal material. The sleeve 5 holds an intermediate portion, along the direction of the axis CL1, of the ceramic heater 4. A forward end portion of the ceramic heater 4 projects and is exposed from the forward end of the sleeve 5. Furthermore, the sleeve 5 is joined to the housing 2 through laser welding along the outer circumference of the contact surface between the housing 2 and the sleeve 5 in a state in which a rear end portion of the sleeve 5 is inserted into the axial bore 7.

[0063] Next, the ceramic heater 4 will be described in detail. As shown in FIG. 3, the ceramic heater 4 includes the round rodlike substrate 21 extending rearward from the forward end of the ceramic heater 4 along the direction of the axis CL1, and a heat-generating element 22 embedded in the substrate 21. The substrate 21 is formed from an electrically insulating ceramic (e.g., silicon nitride or alumina or a like). The heat-generating element 22 is formed from an electrically conductive ceramic which contains silicon nitride as a main component, and an electrically conductive material (in the present embodiment, a silicide, a nitride, or a carbide of molybdenum or tungsten).

[0064] The heat-generating element 22 includes a heat-generating portion 23 disposed in a forward end portion of the substrate 21, and a pair of rodlike lead portions 24 and 25 extending rearward from respective rear ends of the heat-generating portion 23. The heat-generating portion 23 functions as a so-called heat-generating resistor and has a shape resembling the letter U so as to follow the curved surface of a curved forward end portion of the ceramic heater 4. More specifically, the U-shaped heat-generating portion 23 has a turnback subportion 231 provided at its front end side and straight subportions 232 and 233 extending from the turnback subportion 231.

[0065] The lead portions 24 and 25 extend rearward substantially in parallel with each other directed toward the rear end portion of the ceramic heater 4. One lead portion 24 has an electrode lead portion 26, located toward its rear end, projecting radially outward in such a manner as to be exposed at the outer circumferential surface of the ceramic heater 4. Similarly, the other lead portion 25 has an electrode lead portion 27, located toward its rear end, projecting radially outward in such a manner as to be exposed at the outer circumferential surface of the ceramic heater 4. The electrode lead portion 26 of the one lead portion 24 is located rearward of the electrode lead portion 27 of the other lead portion 25 with respect to the direction of the axis CL1.

[0066] The exposed surface of the electrode lead portion 26 is in contact with the inner circumferential surface of the connection member 10, thereby establishing electrical communication between the lead portion 24 and the axial rod 3 connected to the connection member 10. Also, the exposed surface of the electrode lead portion 27 is in contact with the inner circumferential surface of the sleeve 5, thereby establishing electrical communication between the lead portion 25 and the housing 2 connected to the sleeve 5. That is, in the present embodiment, the axial rod 3 and the housing 2 function as an anode and a cathode for supplying power to the heat-generating portion 23 of the ceramic heater 4 in the glow plug 1.

[0067] Additionally, in the present embodiment, the heat-generating portion 23 and the lead portions 24 and 25 are formed from the same material (a material which contains silicon nitride and an electrically conductive material). As shown in FIG. 4, as measured in a direction orthogonal to a plane which contains the center axes of the lead portions 24 and 25, a thickness T1 of the heat-generating portion 23 is 30% or less a thickness T2 of the lead portions 24 and 25. Accordingly, the cross-sectional area of the heat-generating portion 23 (the area of a section taken orthogonally to the axis CL1) is far smaller than that of the lead portions 24 and 25. Thus, the (electrical) resistivity of the heat-generating portion 23 can be far higher than that of the lead portions 24 and 25, whereby, upon energization, the temperature of the heat-generating portion 23 can be raised quite quickly.

[0068] The thickness T1 of the heat-generating portion 23 is the thickness of a region of the heat-generating portion 23 having a substantially fixed thickness (an average thickness). Also, the thickness T2 of the lead portions 24 and 25 is the thickness of a region of the lead portions 24 and 25 having a substantially fixed thickness (an average thickness).

[0069] Furthermore, in the present embodiment, the heat-generating portion 23 has a fracture toughness of 4.3 MPa·m^{0.5} or more. The fracture toughness of the heat-generating portion 23 is calculated according to the IF method of JIS R1607.

[0070] Specifically, first, there is specified a **length** between the forward end of the ceramic heater 4 and a position on the surface of the substrate 21 where temperature is the highest upon energization of the ceramic heater 4. Next,

grinding the surface of the ceramic heater 4 (the substrate 21) is started from a direction perpendicular to the direction of the axis CL1 and along an overlapping direction of the straight subportions 232 and 233 of the heat-generating portion 23 (in other words, grinding is started in the horizontal direction from the right side or the left side on the paper on which FIG. 3 appears), and grinding is continued until the center of the width (the horizontal length on the paper on which FIG. 3 appears) of one of the straight subportion 232 or 233 is reached. Furthermore, on the resultant ground surface located at the center of the width, finish-polishing is performed so as to impart a surface roughness of $0.100\text{ }\mu\text{mRa}$ or less to the surface, thereby forming a surface-to-be-measured S of the heat-generating portion 23 (see FIG. 17). Then, a diamond indenter is driven with a predetermined indentation load P (2 kgf) for a predetermined time (15 seconds) on the surface-to-be-measured S of the heat-generating portion 23 at a position P (see FIG. 17) corresponding to the above-specified length A. Subsequently, by use of a tool maker's microscope (400 magnifications), there are measured the lengths of the diagonals of an indentation marked on the surface-to-be-measured S of the heat-generating portion 23, and the lengths of cracks extending from corners of the indentation. Also, half "a" (m) of the average of the lengths of the diagonals, and half "C" (m) of the average of the lengths of the cracks are calculated. Finally, the indentation load P and the lengths "a" and "C" are substituted into the expression $K_c = 0.026 \times E^{1/2} \times p^{1/2} \times a/C^{3/2}$, thereby obtaining the fracture toughness K_c ($\text{MPa}\cdot\text{m}^{0.5}$). In the present embodiment, the modulus of elasticity E is set to 395×10^9 Pa (395 GPa).

[0071] A portion of the surface of the substrate 21 which corresponds to the heat-generating portion 23 (a portion of the surface located around the extreme heat-generating portion 23) is the "heating portion" in the present invention. However, a portion of the surface of the substrate 21 whose temperature becomes the highest upon energization (in the present embodiment, a portion of the surface located 2 mm rearward from the forward end of the substrate 21) may be the "heating portion."

[0072] Next, a method of manufacturing the glow plug 1 described above will be described, centering on a method of manufacturing the ceramic heater 4. For those members, i.e., components, whose manufacturing methods are not particularly mentioned herein, conventionally known manufacturing methods are employed.

[0073] As shown in FIG. 5, first, in a material preparation step (S1), a silicon nitride powder is added to an electrically conductive material (e.g., a carbide of W); the resultant mixture is slurried in water; and the resultant slurry is spray-dried. To the dried powder, a binder, a plasticizer, a dispersant, etc., are added, followed by mixing so as to yield a powdery element material.

[0074] Next, in a green element body forming step (S2), a green element body 32 (see FIG. 6) which is to become the heat-generating element 22 is formed. Specifically, as shown in FIGS. 7A and 7B, a first mold 51 and a second mold 52 are mated with each other. A heated liquid element material M1 is then injected into a cavity 53 corresponding to the shape of the heat-generating element 22 that is formed in the molds 51 and 52. Subsequently, the injection-molded element material M1 is dried and solidified at a predetermined temperature (e.g., 100°C to 250°C), thereby yielding the green element body 32 having, at its forward end portion, a prospective heat-generating portion 33 which is to become the U-shaped heat-generating portion 23.

[0075] In a halved green insulation body forming step (S3), separately from formation of the green element body 32, a halved green insulation body 31X (see FIG. 6) corresponding to half of the substrate 21 is formed. First, a mixture of an electrically insulating ceramic (e.g., silicon nitride) powder and a sintering aid is slurried in water; a binder is added to the slurry; and the resultant slurry is spray-dried, thereby yielding a substrate material. Next, as shown in FIG. 8, the halved green insulation body 31X is formed by use of a tubular outer frame 61 having an inner space having a rectangular cross section. A lower mold 62 is disposed on a side toward one opening of the outer frame 61. An upper mold 63 is disposed on a side toward the other opening of the outer frame 61 and is vertically movable in relation to the outer frame 61.

[0076] A portion of the lower mold 62 to be disposed within the outer frame 61 has a curved surface corresponding to the outer surface of the halved green insulation body 31X. Also, as shown in FIG. 9, a portion of the upper mold 63 to be disposed within the outer frame 61 has, on its surface, a forming protrusion 63A having a shape resembling the letter U as viewed in plane for forming an accommodation cavity 31A (see FIG. 6) which accommodates half of the green element body 32. Furthermore, the upper mold 63 has rectangular-parallelepiped protrusions 63B and 63C located on opposite sides of a portion of the forming protrusion 63A adapted to form an accommodation cavity which accommodates the prospective heat-generating portion 33.

[0077] In formation of the halved green insulation body 31X, as shown in FIG. 10, in a state in which the outer frame 61 and the lower mold 62 are assembled together, a substrate material M2 is charged in a predetermined amount from the upper opening of the outer frame 61. Next, the upper mold 63 is disposed in such a manner as to close the upper opening of the outer frame 61. The upper mold 63 is then moved toward the lower mold 62 so as to press the substrate material M2 under a predetermined load. This procedure yields, as shown in FIG. 6, the halved green insulation body 31X having the accommodation cavity 31A formed by the forming protrusion 63A, and cavities 31B and 31C formed by the protrusions 63B and 63C.

[0078] Next, in a holding body forming step (S4), a holding body 30 (see FIG. 11) is formed by use of the halved green insulation body 31X, the green element body 32, and the substrate material M2. As shown in FIG. 12, the holding body

forming step uses an outer frame 71 having an inner space having a rectangular cross section. A lower mold 72 is disposed on a side toward one opening of the outer frame 71. An upper mold 73 is disposed on a side toward the other opening of the outer frame 71 and is vertically movable in relation to the outer frame 71. A surface of the lower mold 72 and a surface of the upper mold 73 which are disposed within the outer frame 71 are curved so as to correspond to the outer surface of the holding body 30. The outer frame 71 has inclined surfaces 71A inclined inward and formed on its upper end surface at positions located on opposite sides of the prospective heat-generating portion 33 to be disposed.

[0079] In formation of the holding body 30, first, the outer frame 71 and the lower mold 72 are assembled together, and then the halved green insulation body 31X is set on the lower mold 72. Then, as shown in FIG. 6, the green element body 32 is placed in the accommodation cavity 31A of the halved green insulation body 31X. Subsequently, the substrate material M2 is charged into the outer frame 71 in such a manner as to cover the green element body 32. At this time, the substrate material M2 is also charged onto the inclined surfaces 71A, and, since the cavities 31B and 31C of the halved green insulation body 31X are filled with the substrate material M2, the associated charged substrate material M2 in the region near cavities 31B, 31C is thicker than the substrate material M2 charged in the other regions. Next, the lower mold 72 is moved downward in relation to the outer frame 71, whereby the substrate material M2 charged in the outer frame 71 moves downward. Accordingly, as shown in FIG. 13, the substrate material M2 on the inclined surfaces 71A slides down into the outer frame 71. Subsequently, the upper mold 73 is disposed in such a manner as to close the upper opening of the outer frame 71 and is then moved toward the lower mold 72 so as to press the substrate material M2 under a predetermined load. As a result, as shown in FIG. 11, there is yielded the holding body 30 configured such that the green element body 32 is held within a green insulation body 31. Notably, the packing density of a portion of the green insulation body 31 located around the prospective heat-generating portion 33 is increased through the synergy of the following: as mentioned above, the substrate material M2 charged on the inclined surfaces 71A slides down into the outer frame 71, and the substrate material M2 is charged in a relatively large amount in the cavities 31B and 31C.

[0080] Next, in a debinding step (S5), the holding body 30 is heated at a predetermined temperature (e.g., about 800°C) in a nitrogen gas atmosphere, thereby removing the plasticizer and the binder from the green element body 32 and the green insulation body 31. Meanwhile, since a portion of the green insulation body 31 located around the prospective heat-generating portion 33 has a relatively high packing density, in the present embodiment, after the debinding step, a portion of the green insulation body 31 located around the prospective heat-generating portion 33 has a relative density of 46.3% or more. The term "relative density" means a proportion of the density of the green insulation body 31 located around the prospective heat-generating portion 33 expressed as a percent of the theoretical density of the substrate material M2 as measured after the debinding step.

[0081] Next, in a parting agent application step (S6), a parting agent is applied to the entire outer surface of the holding body 30.

[0082] Then, the holding body 30 is subjected to a firing step (S7). In this step, firing is performed by a so-called hot pressing process. Specifically, by use of an unillustrated hot pressing machine, the holding body 30 is heated under pressure in a non-oxygen atmosphere under, for example, the following conditions: heating temperature 1,800°C; heating time 1.5 hours; and hot pressing pressure 25 MPa. By this procedure, a fired body 40 shown in FIG. 14B is yielded. In order for the fired body 40 to have a substantially circular columnar shape, the firing step uses a carbon jig having a cavity whose shape corresponds to the external form of the above-mentioned ceramic heater 4. Also, as represented by the arrows in FIG. 14A, the holding body 30 is uniaxially pressed.

[0083] Subsequently, in a grinding step (S8), the fired body 40 undergoes various types of grinding, thereby yielding the above-mentioned ceramic heater 4. The employed types of grinding include centerless grinding for grinding the outer circumferential surface of the fired body 40 by use of a publicly known centerless grinding machine, so as to expose the electrode lead portions 26 and 27 from the outer circumferential surface, and R-grinding for imparting a curved surface to a forward end portion of the fired body 40 so as to establish a uniform distance between the extreme heat-generating portion 23 and the outer circumferential surface of the forward end portion.

[0084] Then, the thus-manufactured ceramic heater 4 is assembled with the housing 2 and other members manufactured by publicly known methods. By this procedure, the above-mentioned glow plug 1 is yielded.

[0085] As described in detail above, according to the present embodiment, the heat-generating portion 23 whose temperature becomes high upon energization has a fracture toughness of 4.3 MPa·m^{0.5} or more. Thus, the heat-generating portion 23 has such a high strength as to resist, over a long period of time, a very large thermal stress which is repeatedly applied thereto. As a result, even upon energization for heating under the condition of ultrahigh-speed temperature raising, the occurrence of an electrical disconnection in the heat-generating element 22 (the heat-generating portion 23) can be effectively restrained, whereby the ceramic heater 4 can provide long service life.

[0086] Also, in the present embodiment, the same material is used to form the heat-generating portion 23 and the lead portions 24 and 25. In the case where different materials are used to form the heat-generating portion 23 and the lead portions 24 and 25, there is involved concern about the occurrence of damage at the joints therebetween, and concern about a drop in productivity. However, the present embodiment can eradicate such concerns.

[0087] Additionally, since the thickness T1 of the heat-generating portion 23 is 30% or less than the thickness T2 of

the lead portions 24 and 25, the electrical resistivity of the extreme heat-generating portion 23 can be far more higher than that of the lead portions 24 and 25. Thus, at the time of energization, the temperature of the heat-generating portion 23 can be raised quite quickly, so that ultrahigh-speed temperature raising (the temperature of the surface of the substrate is raised to 1,000°C or higher within one second) can be implemented relatively easily.

[0088] Furthermore, as measured after the debinding step and before the firing step, a portion of the green insulation body 31 located around the prospective heat-generating portion 33 has a relative density of 46.3% or more. Therefore, in the firing step, a large pressure can be applied from the green insulation body 31 to the prospective heat-generating portion 33, whereby there can be accelerated the grain growth of silicon nitride which constitutes the green element body 32. As a result, the fracture toughness of the heat-generating portion 23 can be more reliably increased, so that the ceramic heater 4 having superior durability against ultrahigh-speed temperature raising can be more reliably manufactured.

[0089] Next, in order to verify actions and effects to be yielded by the above embodiment, there were manufactured ceramic heater samples which differed in the fracture toughness of the heat-generating portion as effected through change of the relative density of a portion of the green insulation body located around the prospective heat-generating portion. The samples were subjected to a durability evaluation test. The durability evaluation test is outlined below. The samples were measured for the number of test cycles (electrical-disconnection cycles) until an electrical disconnection occurred in the heat-generating portion. One test cycle consisted of one-second energization conducted so as to raise the temperature of the substrate surface (heating portion) from room temperature to 1,000°C in 0.5 second and such that the substrate surface reaches a maximum temperature of 1,350°C at the temperature-raising gradient, and subsequent air blast cooling for 30 seconds. The samples which exhibited 50,000 electrical-disconnection cycles or more were evaluated as "Good," indicating that the samples were superior in durability against quick temperature raising. Meanwhile, the samples which exhibited less than 50,000 electrical-disconnection cycles were evaluated as "Poor," indicating that the samples were somewhat inferior in durability against quick temperature raising. Table 1 shows the results of the durability evaluation test.

[0090] In order to measure the aforementioned relative density, separately from the above samples subjected to the durability evaluation test, green assemblies were manufactured under the same manufacturing conditions as those of the samples. After the debinding step, as shown in FIG. 15, a forward end portion (a portion located around the prospective heat-generating portion and hatched in FIG. 15) of the green insulation body of each of the manufactured green assemblies was cut out. On the basis of the mass and volume of the cutout, the relative density of the cutout was calculated.

[0091]

Table 1

No.	Fracture toughness (MPa·m ^{0.5})	Relative density (%)	Evaluation
1	3.9	45.0	Poor
2	4.2	45.7	Poor
3	4.3	46.3	Good
4	4.4	47.1	Good
5	4.5	47.8	Good

[0092] As is apparent from Table 1, the samples having a fracture toughness of 4.3 MPa·m^{0.5} or more (samples 3 to 5) have superior durability against quick temperature raising. Conceivably, this is for the following reason: the heat-generating portion had such a high strength as to resist, over a long period of time, a very large thermal stress which is repeatedly applied thereto.

[0093] Also, the following has been confirmed: the establishment of a relative density of 46.3% or more as measured after the debinding step more reliably ensures that the heat-generating portion can have a fracture toughness of 4.3 MPa·m^{0.5} or more. Conceivably, this is for the following reason: by virtue of the relative density being increased, in the firing step, the green insulation body applied a higher pressure to the prospective heat-generating portion; as a result, in the prospective heat-generating portion, the grain growth of silicon nitride was accelerated.

[0094] From the above test results, preferably, in order to implement superior durability against quick temperature raising, the heat-generating portion has a fracture toughness of 4.3 MPa·m^{0.5} or more.

[0095] Also, in order to increase the fracture toughness of the heat-generating portion to such an extent as to have sufficient durability against quick temperature raising, preferably, as measured after the debinding step and before the firing step, a portion of the green insulation body located around the prospective heat-generating portion has a

relative density of 46.3% or more.

[0096] The present invention is not limited to the above-described embodiment, but may be embodied, for example, as follows. Of course, applications and modifications other than those exemplified below are also possible.

[0097] (a) In the above-described embodiment, the fracture toughness of the heat-generating portion 23 is increased through increase of the relative density of the green insulation body 31. However, a technique for increasing fracture toughness is not limited thereto. For example, the following technique may be employed: the grain growth of silicon nitride is accelerated through adjustment of the heating temperature and the heating time in the firing step, thereby increasing the fracture toughness of the heat-generating portion 23 to $4.3 \text{ MPa}\cdot\text{m}^{0.5}$ or more.

[0098] (b) In the above-described embodiment, by means of forming the cavities 31B and 31C in the halved green insulation body 31X, etc., in the holding body forming step, more substrate material M2 is charged around the prospective heat-generating portion 33, thereby increasing the relative density of a portion of the green insulation body 31 located around the prospective heat-generating portion 33. Alternatively, in order to increase the relative density, for example, as shown in FIG. 16, in the holding body forming step, the holding body 30 may be formed by use of a lower mold 82 having a downward gradient toward a region where the prospective heat-generating portion 33 is disposed. Specifically, in a state in which the lower mold 82 and an outer frame 81 are assembled together, the halved green insulation body 31X is placed on the lower mold 82, and the green element body 32 is disposed in the accommodation cavity 31A. Then, the substrate material M2 is charged into the outer frame 81, and an upper mold 83 is moved toward the lower mold 83 so as to press the substrate material M2, etc. In this case, the substrate material M2 is charged more toward the region where the prospective heat-generating portion 33, and, by virtue of the presence of gradient on the lower mold 82, in the course of pressing, the substrate material M2 is pressed toward the prospective heat-generating portion 33. Therefore, a portion of the green insulation body 31 located around the prospective heat-generating portion 33 can have an increased relative density.

[0099] (c) In the above-described embodiment, the green element body 32 is formed by injection molding. However, another forming method may be employed for forming the green element body. For example, the green element body may be formed as follows: an element material which contains a predetermined binder is formed into an electrically conductive sheet, and the green element body is punched out from the electrically conductive sheet by use of a predetermined die. Alternatively, the green element body may be formed as follows: an element material is mixed with a predetermined binder and a solvent so as to form a slurry, and the slurry is poured into an accommodation cavity of the halved green insulation body, followed by drying (volatilization of the solvent) to yield the green element body.

[0100] (d) In the ceramic heater 4 of the above-described embodiment, the same material is used to form the heat-generating portion 23 and the lead portions 24 and 25. However, the heat-generating portion 23 and the lead portions 24 and 25 are not necessarily formed from the same material, but may be formed from different materials. In this case, by means of imparting a fracture toughness of $4.3 \text{ MPa}\cdot\text{m}^{0.5}$ or more to the heat-generating portion 23, superior durability against quick temperature raising can be implemented.

[0101] (e) The ceramic heater 4 of the above-described embodiment has a rodlike shape having a circular cross section. However, the cross-sectional shape is not necessarily a circle. For example, the cross section may have an elliptical shape, an elongated circular shape, or a polygonal shape. Also, the technical ideas of the present invention may be applied to a so-called sheet heater configured such that a heat-generating body is sandwiched between electrically insulating sheet substrates.

Claims

1. A ceramic heater comprising:

a substrate formed from an electrically insulating ceramic and extending rearward from a forward end of the ceramic heater in a direction of an axis, and
a heat-generating element having a heat-generating portion formed from an electrically conductive ceramic which contains silicon nitride and an electrically conductive material, said heat-generating portion disposed in a forward end portion of the substrate, and having a shape resembling a letter U as viewed along the direction of the axis,
wherein the heat-generating portion has a fracture toughness of $4.3 \text{ MPa}\cdot\text{m}^{0.5}$ or more.

2. A ceramic heater according to claim 1, wherein:

the heat-generating element has electrically conductive lead portions connected to respective ends of the heat-generating portion, said lead portions located on the rear end side of the heat-generating portion, and
a thickness of the heat-generating portion is equal to 30% or less than that of the lead portions.

3. A ceramic heater according to claim 2, wherein the heat-generating portion and the lead portions are formed from the same material.

4. A heating apparatus comprising:

a ceramic heater according to any one of claims 1 to 3, and
an energization control unit configured to adjust supply power to the heat-generating element, and adapted to control heat generation of the heat-generating portion through adjustment of the supply power,
wherein the energization control unit supplies power to the heat-generating element in such a manner as to raise a surface temperature of a heating portion of the substrate corresponding to the heat-generating portion from a room temperature to 1,000°C within one second.

5. A method of manufacturing a ceramic heater which comprises:

a substrate formed from an electrically insulating ceramic extending in a direction of an axis, and
a heat-generating element embedded in the substrate and having a heat-generating portion containing silicon nitride and an electrically conductive material, said heat-generating portion disposed in a forward end portion of the substrate and having a shape resembling a letter U as viewed along the direction of the axis,
the method comprising:

forming a green element body which is to become the heat-generating element, said green element body comprised of an element material which contains an electrically conductive material powder and silicon nitride;

forming a holding body in which the green element body is embedded in a green insulation body, said green insulation body formed from a substrate material containing an electrically insulating ceramic powder and which is to become the substrate;

debinding the holding body; and

firing the holding body under pressure;

wherein the green element body has a prospective heat-generating portion which is to become the heat-generating portion, and

as measured after the debinding step and before the firing step, a portion of the green insulation body located around the prospective heat-generating portion has a relative density of 46.3% or more.

6. A method of manufacturing a ceramic heater according to claim 5, wherein the ceramic heater is operable to raise a surface temperature of a heating portion of the substrate corresponding to the heat-generating portion from a room temperature to 1,000°C within one second.

FIG. 1

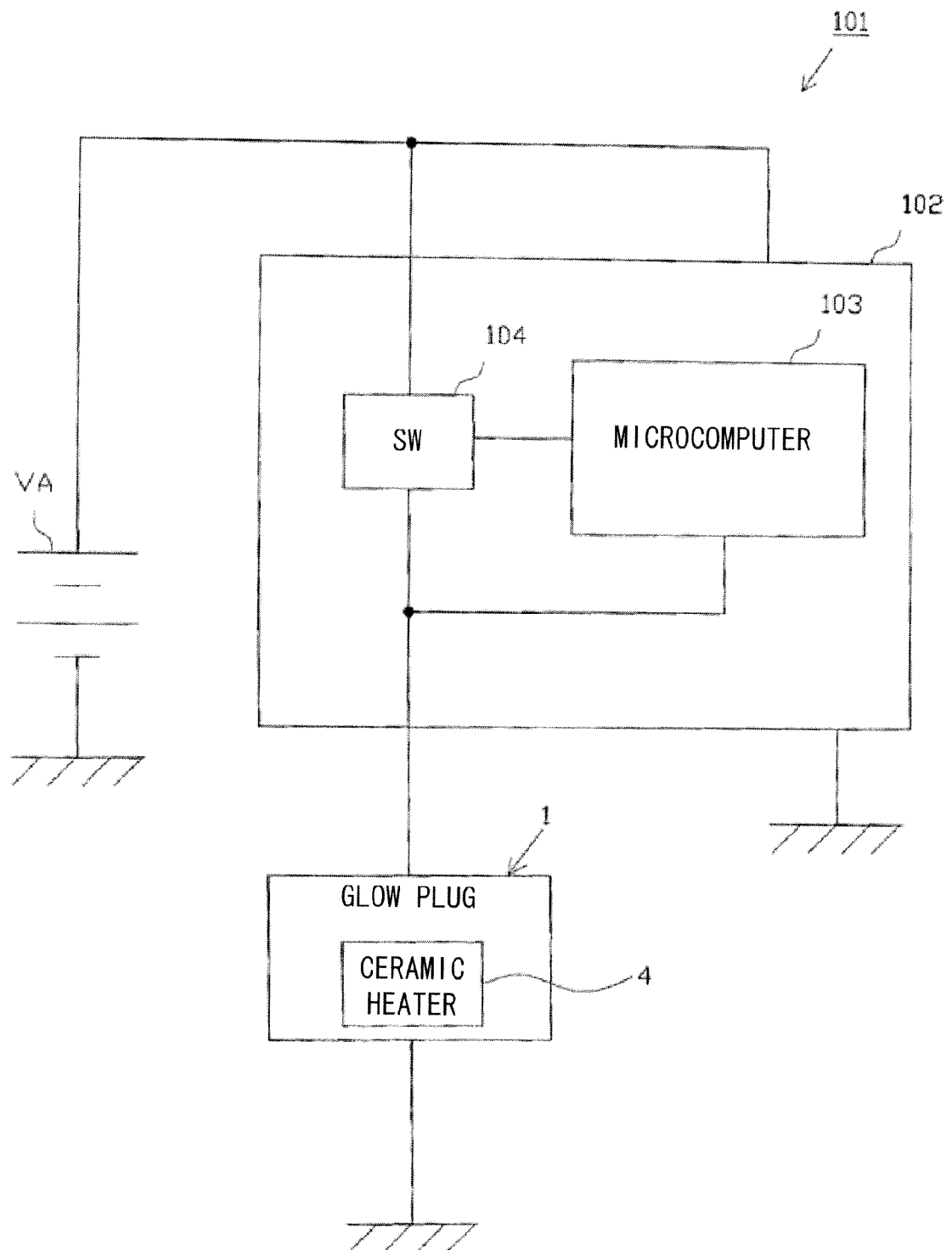


FIG. 2A

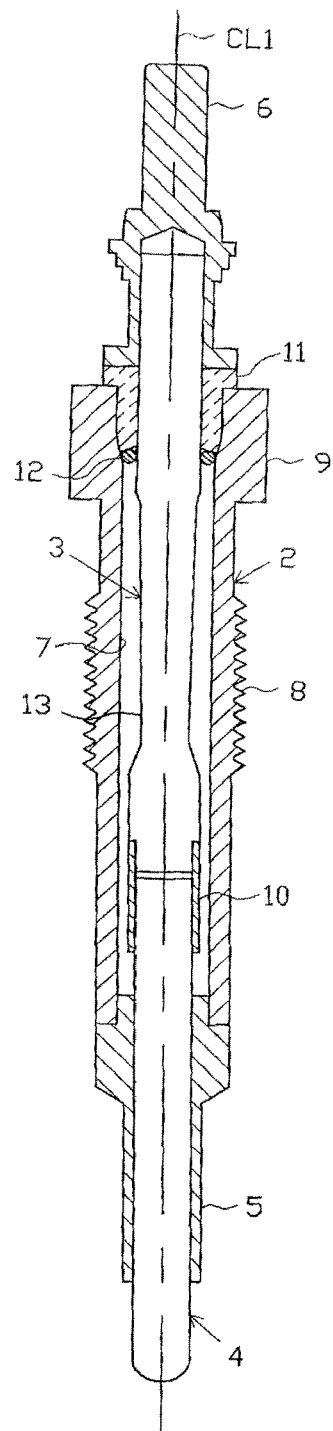


FIG. 2B

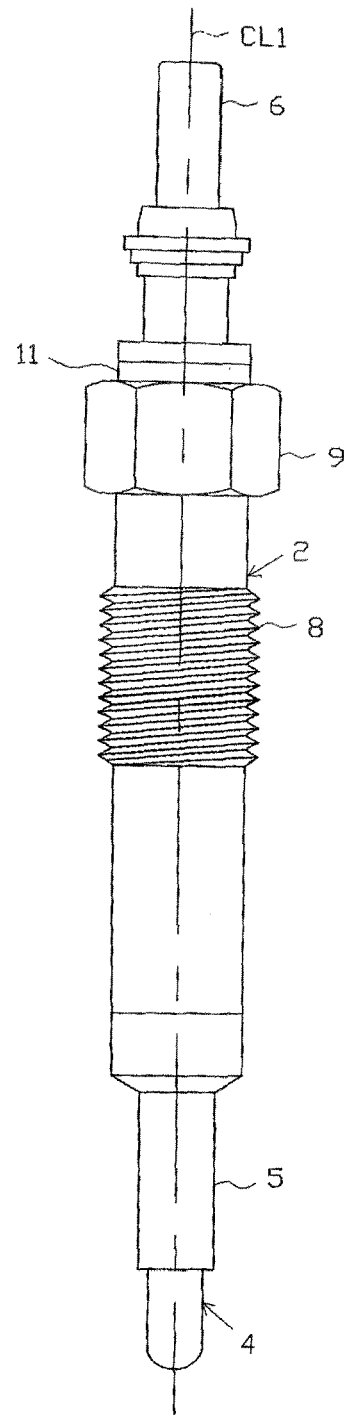


FIG. 3

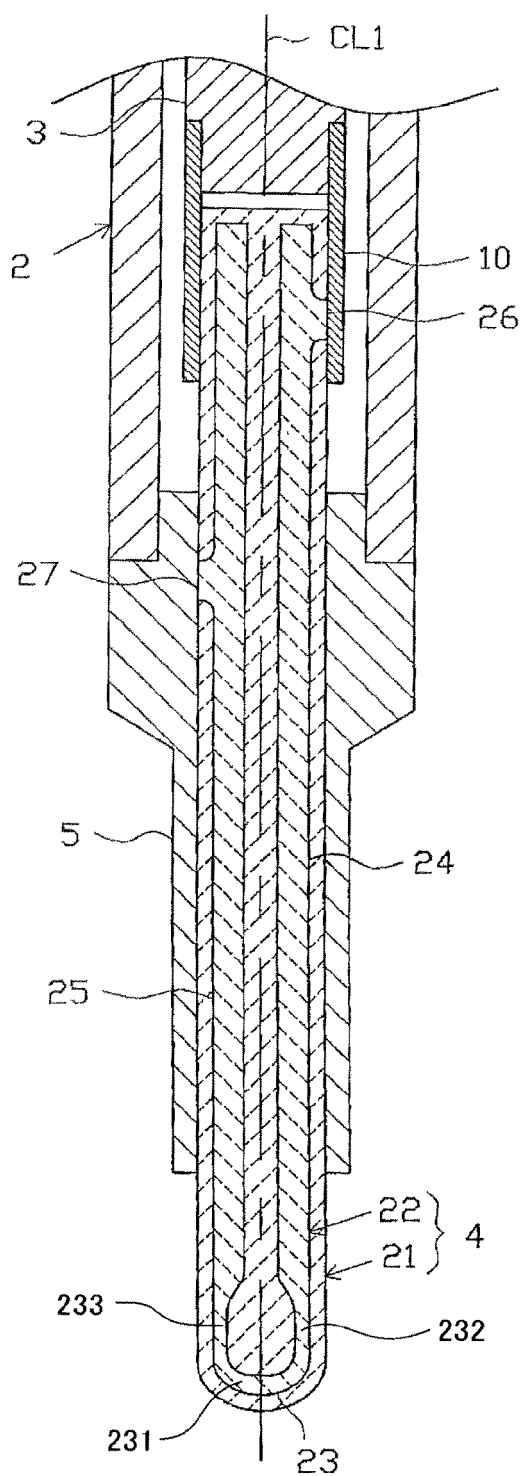


FIG. 4

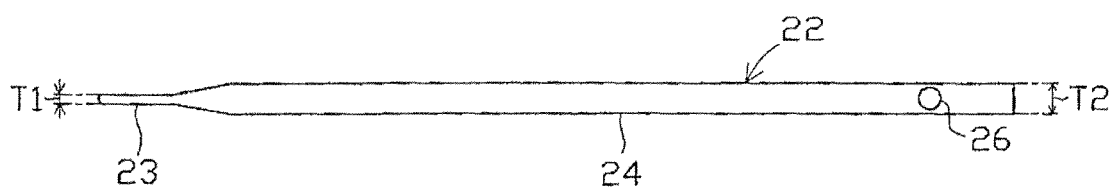


FIG. 5

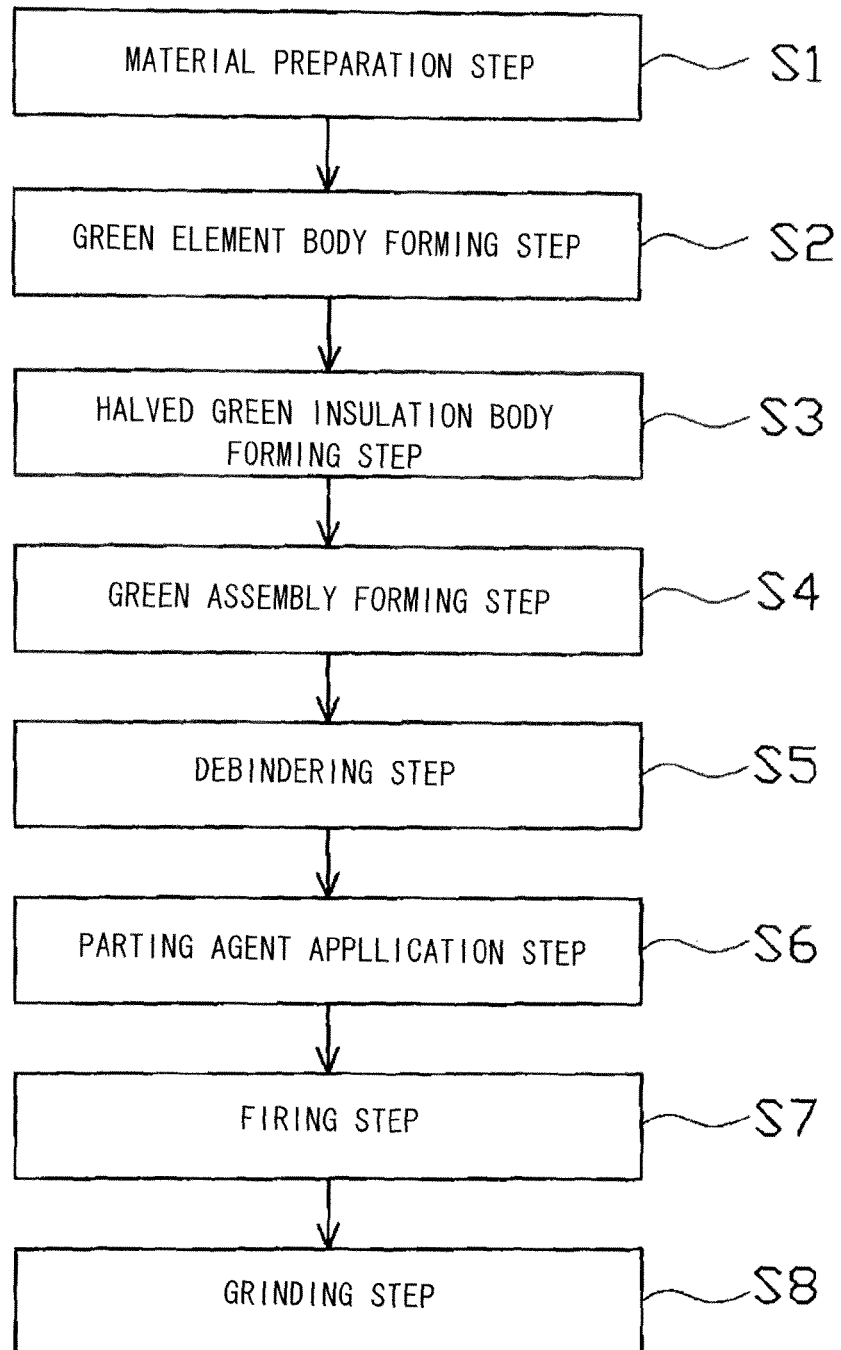


FIG. 6

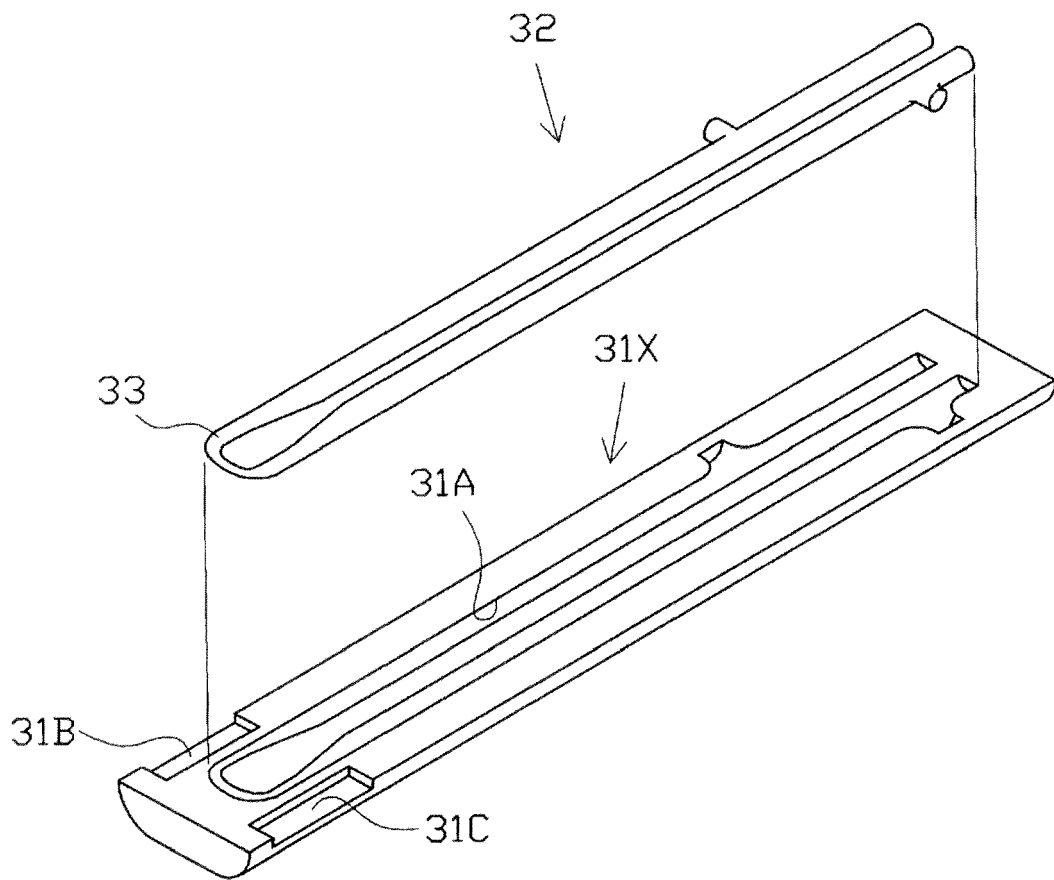


FIG. 7A

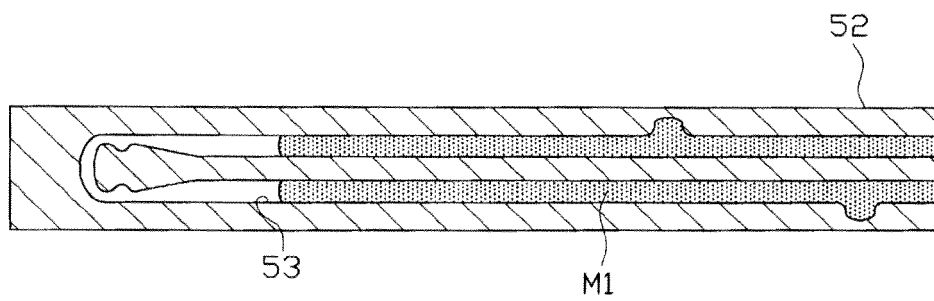


FIG. 7B

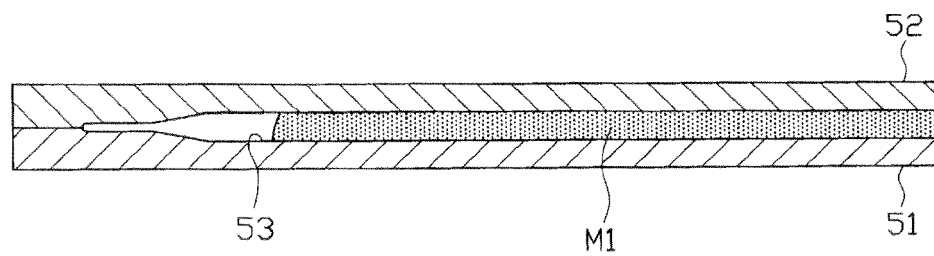


FIG. 8

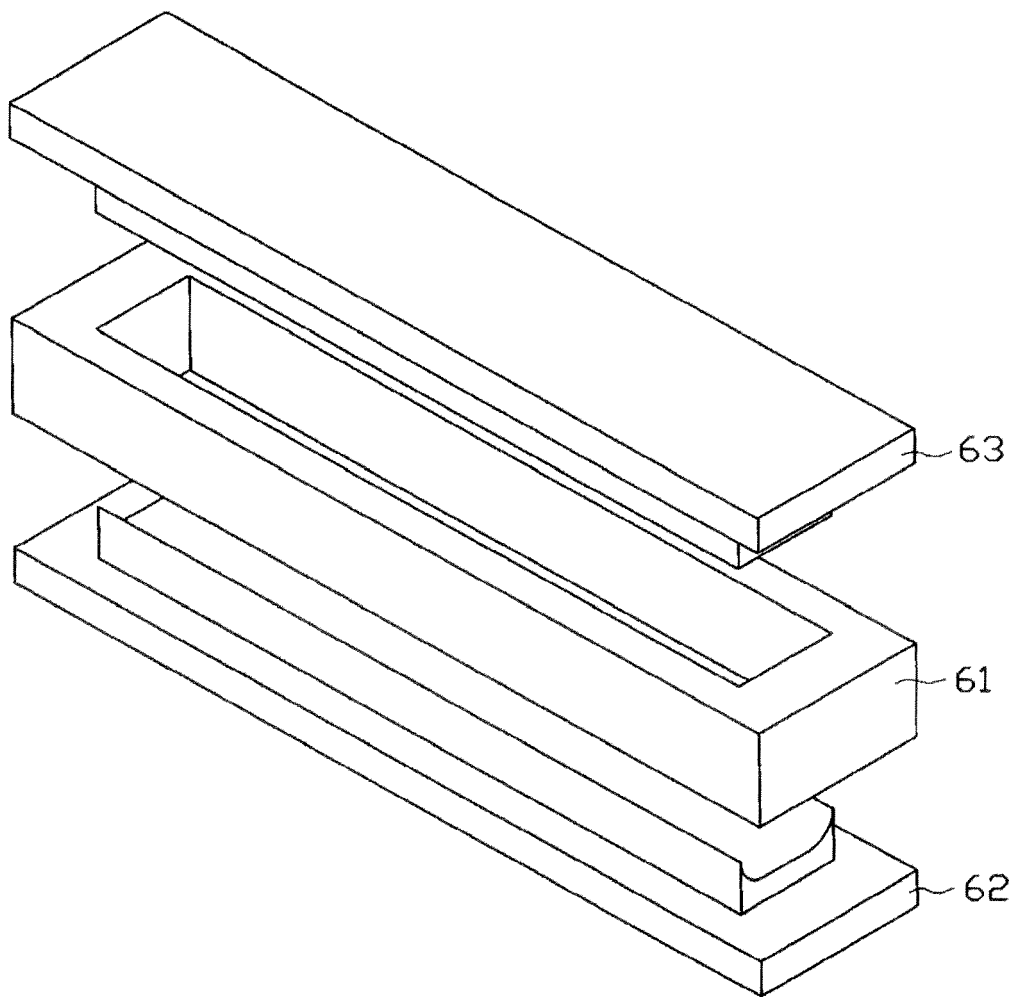


FIG. 9

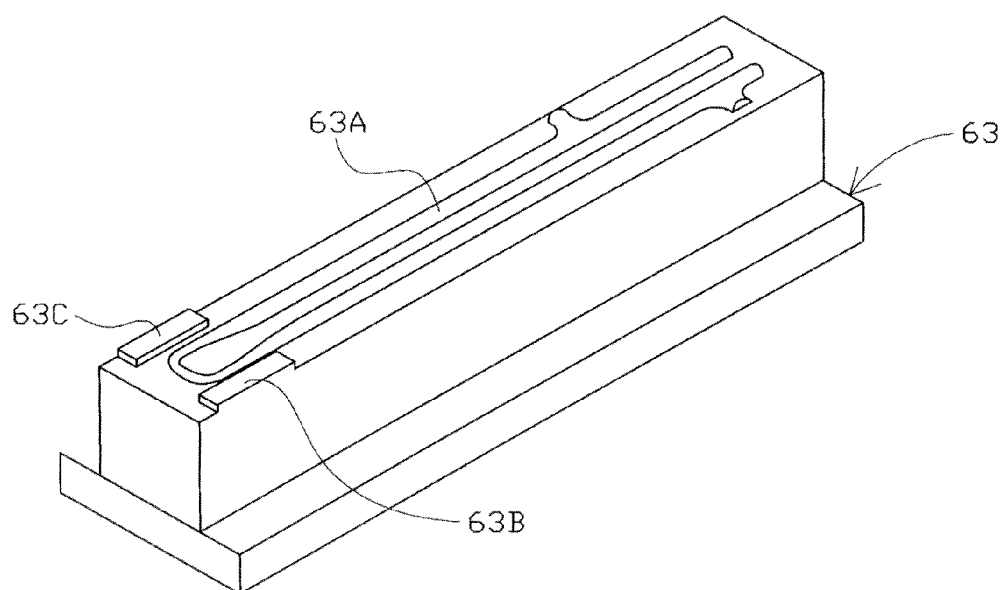


FIG. 10

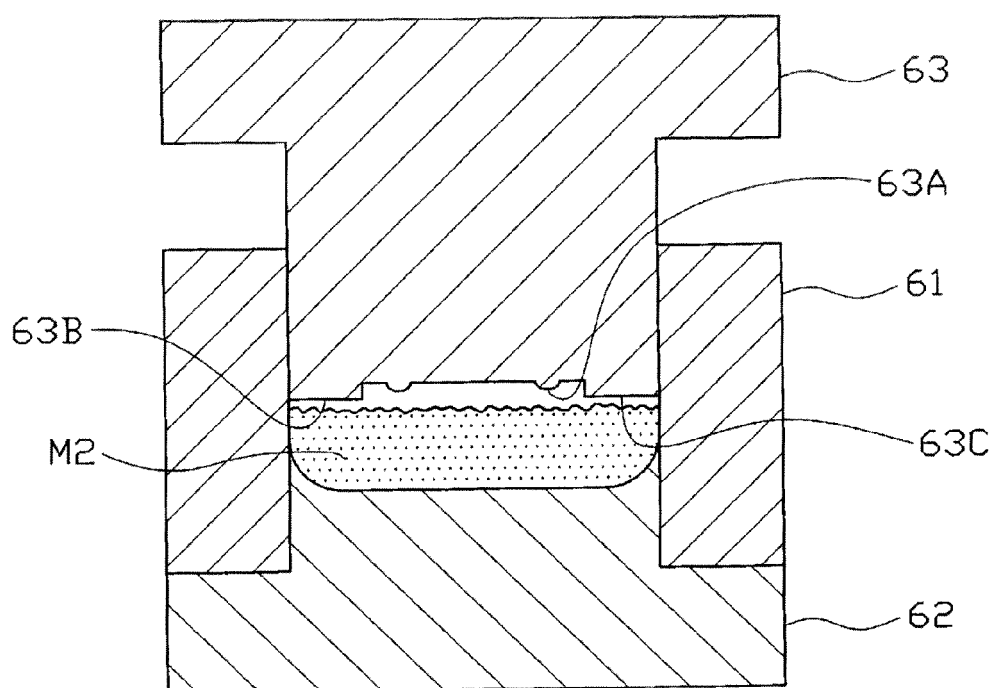


FIG. 11

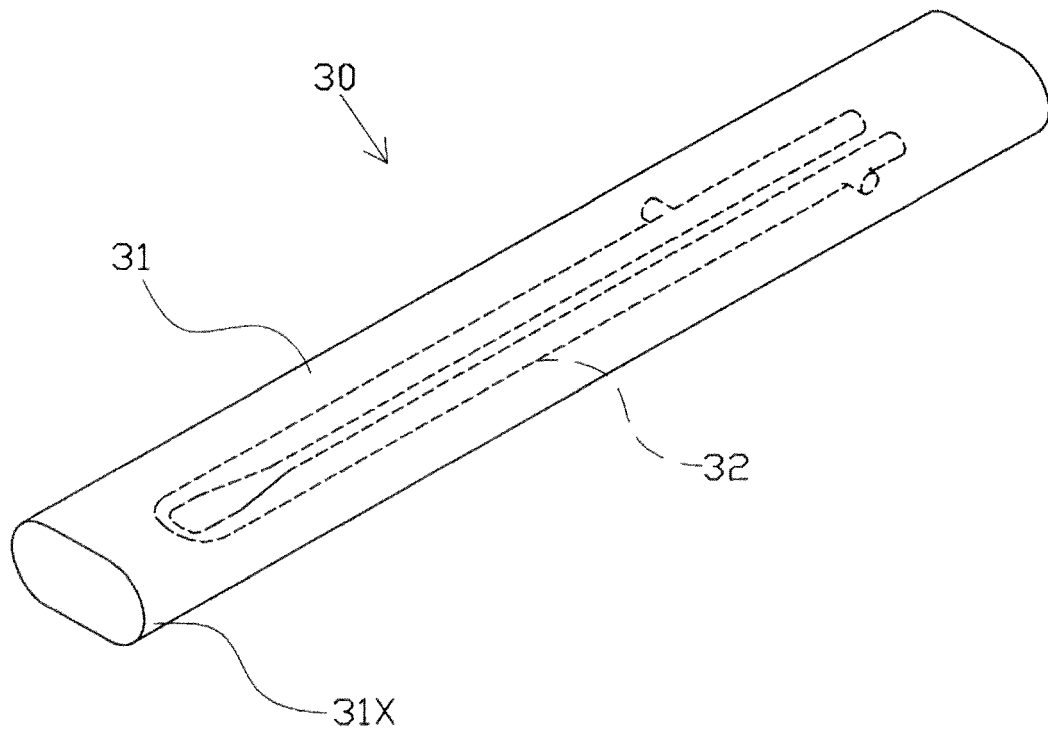


FIG. 12

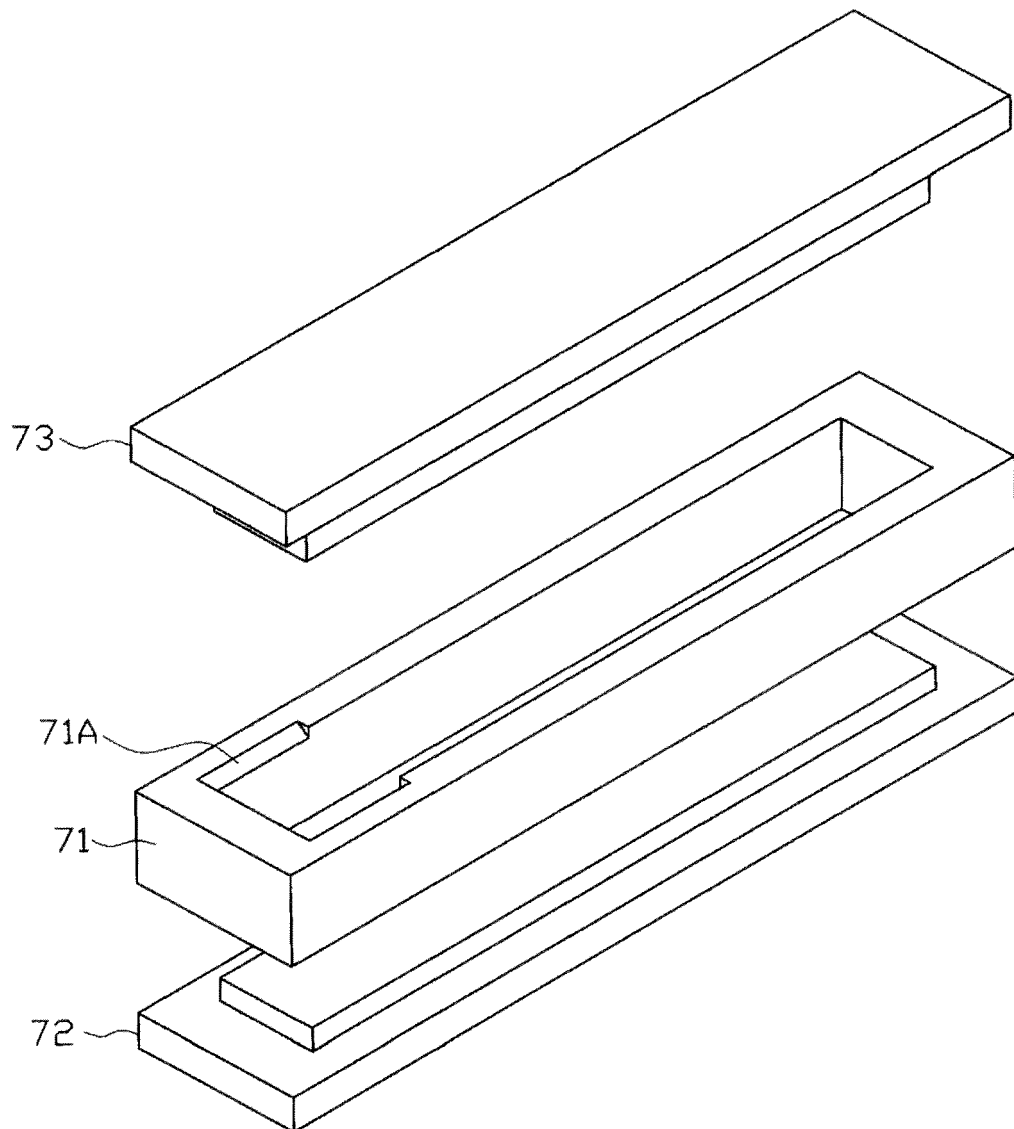


FIG. 13

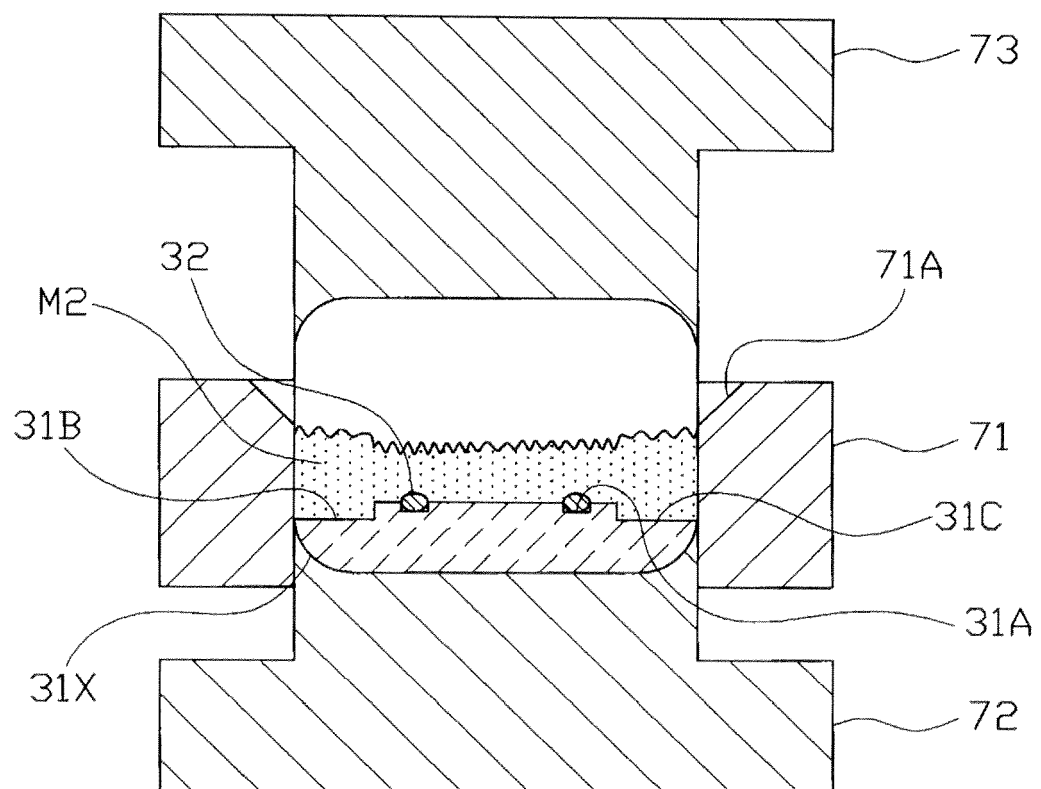


FIG. 14A

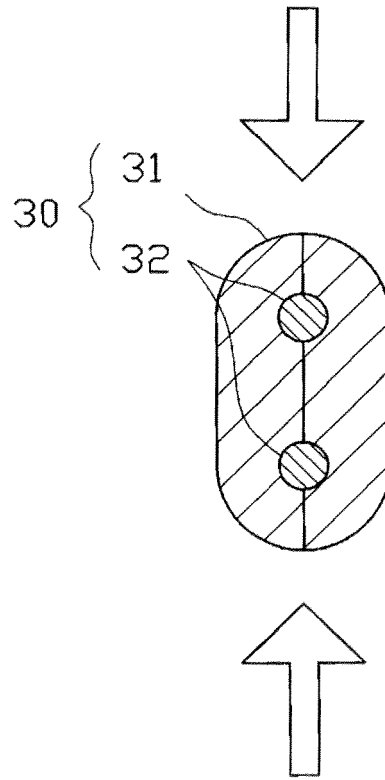


FIG. 14B

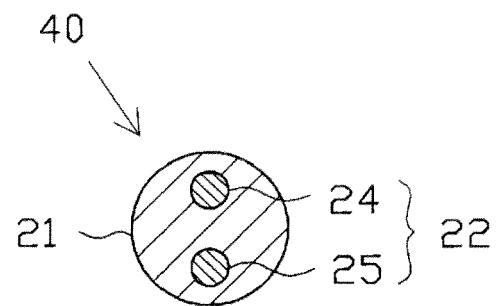


FIG. 15

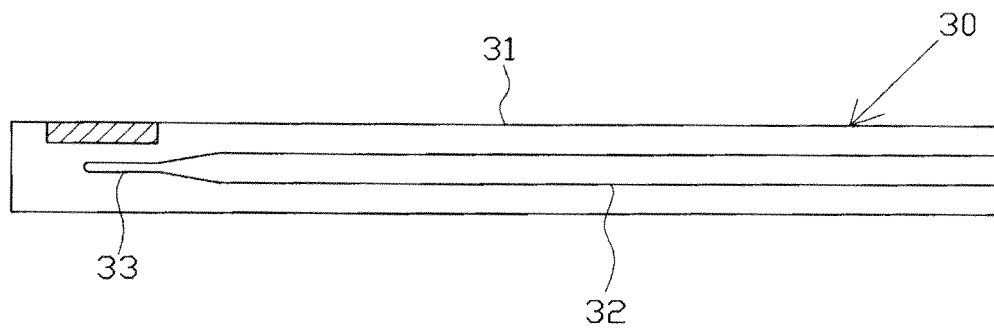


FIG. 16

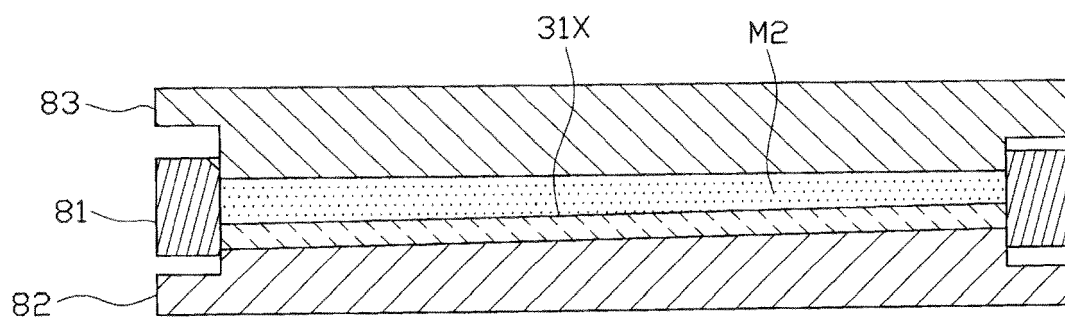
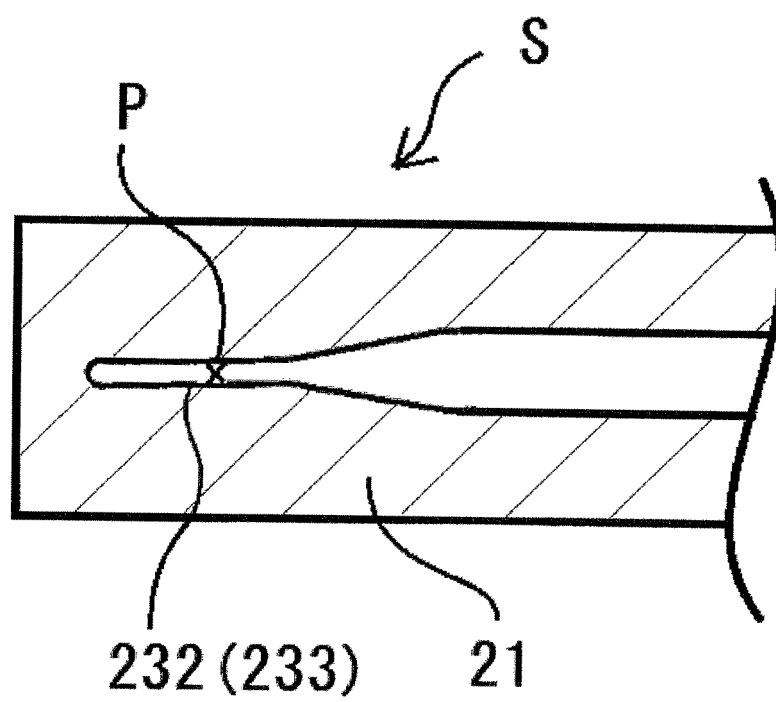


FIG. 17



REFERENCES CITED IN THE DESCRIPTION

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