GAS SENSOR

Abstract

A gas sensor includes a sensor element including an element body, a first measurement pump cell, a second measurement pump cell, an adjustment pump cell, and a reference electrode; and a control apparatus, wherein the control apparatus detects a NOx concentration based on a first measurement pump current which flows when the oxygen produced due to reduction of NOx is pumped out, and the control apparatus detects a carbon dioxide concentration based on a second measurement pump current which flows when the oxygen produced due to reduction of carbon dioxide in a second measurement chamber is pumped out, and a change in a first measurement pump current which flows during execution of a adjustment pump control process and a first measurement pump control process when at least one of an adjustment voltage target value or a first measurement voltage target value is changed.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION [0001] This application is a continuation application of PCT/JP2023/034343, filed on Sep. 21, 2023, which claim the benefit of priority of Japanese Patent Application No. [0002] JP2022-169087, filed on Oct. 21, 2022, the entire contents of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION
1. Field of the Invention
[0003] The present invention relates to a gas sensor.
2. Description of the Related Art
[0004] Hitherto, a gas sensor that detects the concentration of a specific gas, such as NOx, in a measurement-object gas, such as the exhaust gas of an automobile, is known. For example, PTL 1 describes a gas sensor comprising: an element body which includes an oxygen-ion-conductive solid electrolyte layer, and is internally provided with a measurement-object gas flow portion that introduces a measurement-object gas and causes the measurement-object gas to flow therethrough; and a plurality of electrodes disposed in the element body. When the concentration of NOx is detected by the gas sensor, pumping-out or pumping-in of oxygen is first performed between an oxygen concentration adjustment chamber of the measurement-object gas flow portion, and the outside of a sensor element, and the oxygen concentration in the oxygen concentration adjustment chamber is adjusted. The measurement-object gas with the oxygen concentration adjusted reaches a measurement chamber provided downstream of the oxygen concentration adjustment chamber of the measurement-object gas flow portion. In the measurement chamber, the NOx in measurement-object gas is reduced in the periphery of a measurement electrode disposed in the measurement chamber. Then, feedback control is performed on a measurement pump cell so that a voltage V2 generated across the measurement electrode and a reference electrode reaches a predetermined target value, and the oxygen around the measurement electrode is pumped out. The concentration of NOx in the measurement-object gas is detected based on pump current Ip2 which flows then.
[0005] A gas sensor is also known, which detects a carbon dioxide concentration in the measurement-object gas. For example, the gas sensor described in PTL 2 adjusts the oxygen partial pressure in a first internal cavity of a sensor element so that all of the water vapor component and the carbon dioxide component in the measurement-object gas are substantially decomposed in the first internal cavity. The gas sensor then supplies oxygen to a second internal cavity by a first measurement electrochemical pumping cell so that the hydrogen generated by decomposition of the water vapor component is selectively burned in the second internal cavity, and identifies the concentration of the water vapor component present in the measurement-object gas based on the magnitude of a current flowing then. In addition, the gas sensor supplies oxygen to the surface of a second measurement inner electrode by a second measurement electrochemical pumping cell so that the carbon monoxide generated by decomposition of the carbon dioxide component is selectively burned, and identifies the concentration of the carbon dioxide component present in the measurement-object gas based on the magnitude of a current flowing then.

CITATION LIST
Patent Literature
[0006] PTL 1: JP 2022-091669 A [0007] PTL 2: JP 5918177 B
SUMMARY OF THE INVENTION
[0008] However, it has not been known that a gas sensor detecting both the NOx concentration and the carbon dioxide concentration in the measurement-object gas. The present invention has been devised to solve such a problem, and it is a main object to detect the NOx concentration and the carbon dioxide concentration in the measurement-object gas.
[0009] The present invention employs the following device to achieve the above-described main object.
[0010] [1] A gas sensor according to the present invention is a gas sensor comprising: a sensor element including an element body including an oxygen-ion-conductive solid electrolyte layer and internally provided with a measurement-object gas flow portion that receives a measurement-object gas and causes the measurement-object gas to flow therethrough, a first measurement pump cell constituted by including an first inner measurement electrode disposed in a first measurement chamber of the measurement-object gas flow portion, the first measurement pump cell being configured to pump out oxygen in the first measurement chamber to an outside of the element body, a second measurement pump cell constituted by including an second inner measurement electrode disposed in a second measurement chamber located downstream of the first measurement chamber of the measurement-object gas flow portion, the second measurement pump cell being configured to pump out oxygen in the second measurement chamber to an outside of the element body, an adjustment pump cell constituted by including an inner adjustment electrode disposed in an oxygen concentration adjustment chamber located upstream of the first measurement chamber of the measurement-object gas flow portion, the adjustment pump cell being configured to adjust an oxygen concentration in the oxygen concentration adjustment chamber, and a reference electrode disposed inside the element body to come into contact with a reference gas; and a control apparatus that performs an adjustment pump control process of adjusting the oxygen concentration in the oxygen concentration adjustment chamber by controlling the adjustment pump cell so that an adjustment voltage that is a voltage across the reference electrode and the inner adjustment electrode reaches an adjustment voltage target value, a first measurement pump control process of pumping out oxygen in the first measurement chamber by controlling the first measurement pump cell so that a first measurement voltage that is a voltage across the reference electrode and the first inner measurement electrode reaches a first measurement voltage target value, and a second measurement pump control process of pumping out oxygen in the second measurement chamber by controlling the second measurement pump cell so that a second measurement voltage that is a voltage across the reference electrode and the second inner measurement electrode reaches a second measurement voltage target value, wherein the control apparatus detects a NOx concentration in the measurement-object gas based on a first measurement pump current which flows when the oxygen produced due to reduction of NOx in the first measurement chamber is pumped out by the first measurement pump control process, and the control apparatus detects a carbon dioxide concentration in the measurement-object gas based on a second measurement pump current which flows when the oxygen produced due to reduction of carbon dioxide in the second measurement chamber is pumped out by the second measurement pump control process, and a change in the first measurement pump current which flows during execution of the adjustment pump control process and the first measurement pump control process when at least one of the adjustment voltage target value or the first measurement voltage target value is changed.
[0011] In the gas sensor, the control apparatus performs the adjustment pump control process of adjusting the oxygen concentration in the oxygen concentration adjustment chamber by controlling the adjustment pump cell so that the adjustment voltage that is the voltage across the reference electrode and the inner adjustment electrode reaches the adjustment voltage target value. In

addition, the control apparatus performs the first measurement pump control process of pumping out the oxygen in the first measurement chamber by controlling the first measurement pump cell so that the first measurement voltage that is the voltage across the reference electrode and the first inner measurement electrode reaches the first measurement voltage target value. The control apparatus performs the second measurement pump control process of pumping out oxygen in the second measurement chamber by controlling the second measurement pump cell so that the second measurement voltage that is the voltage across the reference electrode and the second inner measurement electrode reaches the second measurement voltage target value. The control apparatus then detects the NOx concentration in the measurement-object gas based on a first measurement pump current which flows when the oxygen produced due to reduction of NOx in the first measurement chamber is pumped out by the first measurement pump control process. In addition, the control apparatus detects the carbon dioxide concentration in the measurement-object gas based on the second measurement pump current which flows when the oxygen produced due to reduction of carbon dioxide in the second measurement chamber is pumped out by the second measurement pump control process, and the change in the first measurement pump current which flows during execution of the adjustment pump control process and the first measurement pump control process when at least one of the adjustment voltage target value or the first measurement voltage target value is changed. In this manner, the gas sensor of the present invention detects the NOx concentration based on the first measurement pump current, and detects the carbon dioxide concentration based on the second measurement pump current. However, if the measurement-object gas contains water, not only carbon dioxide but also water is reduced in the second measurement chamber, so the second measurement pump current which is caused to flow by the second measurement pump control process is a value based on the carbon dioxide concentration and the water concentration. However, the inventors have found that the water concentration in the measurement-object gas correlates with the change in the first measurement pump current when at least one of the adjustment voltage target value or the first measurement voltage target value is changed. Thus, the carbon dioxide concentration in the measurement-object gas can be detected based on the second measurement pump current and the change in the first measurement pump current. Based upon the foregoing, the gas sensor of the present invention can detect the NOx concentration and the carbon dioxide concentration in the measurement-object gas.

[0012] [2] In the above-described gas sensor (the gas sensor according to [1] above), the control apparatus may detect a water concentration in the measurement-object gas based on the change in the first measurement pump current. As described above, the water concentration in the measurement-object gas correlates with the change in the first measurement pump current when at least one of the adjustment voltage target value or the first measurement voltage target value is changed. Thus, the water concentration in the measurement-object gas can be detected based on the change. In this case, the control apparatus may detect a carbon dioxide concentration in the measurement-object gas based on the second measurement pump current and the water concentration detected.

[0013] [3] In the above-described gas sensor (the gas sensor according to [2] above), the control apparatus may derive a total value of a carbon dioxide concentration and a water concentration in the measurement-object gas based on the second measurement pump current, and detect the carbon dioxide concentration in the measurement-object gas by subtracting the water concentration detected from the total value. In this manner, the gas sensor can detect the carbon dioxide concentration using a relatively simple method.

[0014] [4] In the above-described gas sensor (the gas sensor according to any one of [1] to [3] above), the control apparatus may detect the oxygen concentration in the measurement-object gas based on an adjustment pump current which is caused to flow by the adjustment pump control process. In this manner, the gas sensor can detect the oxygen concentration in the measurement-object gas.

[0015] [5] In the above-described gas sensor (the gas sensor according to any one of [1] to [4] above), the oxygen concentration adjustment chamber may have a first internal cavity, and a second internal cavity provided downstream of the first internal cavity and upstream of the measurement chamber, the adjustment pump cell may have a main pump cell that adjusts an oxygen concentration in the first internal cavity, and an auxiliary pump cell that adjusts an oxygen concentration in the second internal cavity, the inner adjustment electrode may have an inner main pump electrode that is disposed in the first internal cavity and constitutes part of the main pump cell, and an inner auxiliary pump electrode that is disposed in the second internal cavity and constitutes part of the auxiliary pump cell, and the adjustment pump control process may include a main pump control process of controlling the main pump cell to adjust the oxygen concentration in the first internal cavity, and an auxiliary pump control process of controlling the auxiliary pump cell so that the adjustment voltage reaches the adjustment voltage target value.

[0016] [6] In the above-described gas sensor (the gas sensor according to any one of [1] to [5] above), the inner adjustment electrode may contain a noble metal with catalytic activity and Au. In this manner, Au contained in the inner adjustment electrode inhibits the catalytic activity for NOx and carbon dioxide, thus reduction of NOx and carbon dioxide in the oxygen concentration adjustment chamber can be inhibited.

[0017] [7] In the above-described gas sensor (the gas sensor according to any one of [1] to [6] above), the first inner measurement electrode may contain Rh and a noble metal with catalytic activity other than Rh. In this manner, the first inner measurement electrode containing Rh can promote the reduction of NOx in the first measurement chamber.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] FIG. **1** is a cross-sectional schematic view schematically showing an example of the configuration of a gas sensor **100**.

[0019] FIG. **2** is a block diagram showing an electrical connection relationship between a control apparatus **95**, cells and a heater **72**.

[0020] FIG. **3** is a graph showing a relationship between target value V**1***, water concentration and pump current Ip**2**.

[0021] FIG. **4** is a graph showing a relationship between water concentration and slope of change in offset current Ip**2**offset for change in target value V**1***.

[0022] FIG. **5** is a graph showing a relationship between target value V**2***, water concentration and pump current Ip**2**.

[0023] FIG. **6** is a graph showing a relationship between water concentration and slope of change in offset current Ip**2**offset for change in target value V**2***.

[0024] FIG. **7** is a flowchart showing an example of a control routine.

[0025] FIG. **8** is a graph showing a relationship between total value Cs of water concentration and carbon dioxide concentration and pump current Ip**2**.

[0026] FIG. **9** is a graph showing a correspondence relationship between slope G, pump current Ip**3**, and carbon dioxide concentration.

[0027] FIG. **10** is a cross-sectional schematic view of sensor element **201**.

DETAILED DESCRIPTION OF THE INVENTION

[0028] Next, an embodiment of the present invention will be described using the drawings. FIG. **1** is a cross-sectional schematic view schematically showing an example of the configuration of gas sensor **100** which is an embodiment of the present invention. FIG. **2** is a block diagram showing an electrical connection relationship between a control apparatus **95**, cells and a heater **72**. The gas sensor **100** is installed in a pipe, such as an exhaust gas pipe of an internal combustion engine, for

example. The gas sensor **100** uses the exhaust gas from an internal combustion engine as the measurement-object gas, and detects the concentration of a specific gas. In the present embodiment, the gas sensor **100** measures a NOx concentration, a carbon dioxide concentration, a water concentration, and an oxygen concentration as the specific gas concentration. The gas sensor **100** has a long rectangular parallelepiped sensor element **101**, cells **21**, **41**, **50**, **80** to **84** included in the sensor element **101**, a heater portion **70** provided inside the sensor element **101**, and a control apparatus **95** that includes variable power supplies **24**, **46**, **52**, **68** and a heater power supply **76**, and controls the entire gas sensor **100**.

[0029] The sensor element **101** is an element having a layered body in which six layers, that is, a first substrate layer **1**, a second substrate layer **2**, a third substrate layer **3**, a first solid electrolyte layer **4**, a spacer layer **5**, and a second solid electrolyte layer **6**, each made up of an oxygen-ion-conductive solid electrolyte layer made of zirconia (ZrO_2) or the like, are laminated in this order from a lower side in the drawing. The solid electrolyte forming these six layers is a dense, airtight one. The sensor element **101** is manufactured by, for example, applying predetermined processing, printing of a circuit pattern, and the like on a ceramic green sheet corresponding to each layer, then laminating those sheets, and further firing the sheets to be integrated.

[0030] At a tip end portion side of the sensor element **101** (left end portion side in FIG. **1**), a gas inlet port **10**, a first diffusion controlled portion **11**, a buffer space **12**, a second diffusion controlled portion **13**, a first internal cavity **20**, a third diffusion controlled portion **30**, a second internal cavity **40**, a fourth diffusion controlled portion **60**, a third internal cavity **61**, and a fifth diffusion controlled portion **62**, and a fourth internal cavity **63** are formed adjacent to each other so as to communicate with each other in this order between the under surface of the second solid electrolyte layer **6** and the top surface of the first solid electrolyte layer **4**.

[0031] The gas inlet port **10**, the buffer space **12**, the first internal cavity **20**, the second internal cavity **40**, the third internal cavity **61**, and the fourth internal cavity **63** are spaces of which top parts, bottom parts, and side parts, provided by hollowing the spacer layer **5**, are respectively defined by the under surface of the second solid electrolyte layer **6**, the top surface of the first solid electrolyte layer **4**, and the side surface of the spacer layer **5** inside the sensor element **101**.

[0032] Each of the first diffusion controlled portion **11**, the second diffusion controlled portion **13**, and the third diffusion controlled portion **30** is provided as two laterally long slits (openings of which the longitudinal direction is a direction perpendicular to the drawing). Each of the fourth diffusion controlled portion **60** and the fifth diffusion controlled portion **62** is provided as a single laterally long slit (an opening of which the longitudinal direction is a direction perpendicular to the drawing) formed as a clearance from the under surface of the second solid electrolyte layer **6**. A part from the gas inlet port **10** to the fourth internal cavity **63** is also referred to as measurement-object gas flow portion.

[0033] At a location farther from the tip end side than the measurement-object gas flow portion, a reference gas inlet space **43** is provided between the top surface of the third substrate layer **3** and the under surface of the spacer layer **5** at a location at which the side part is defined by the side surface of the first solid electrolyte layer **4**. For example, the atmosphere is introduced into the reference gas inlet space **43** as a reference gas at the time of measuring a NOx concentration.

[0034] A reference gas inlet layer **48** is a layer made of porous ceramics. The reference gas is introduced into the reference gas inlet layer **48** through the reference gas inlet space **43**. The reference gas inlet layer **48** is formed so as to coat the reference electrode **42**.

[0035] The reference electrode **42** is an electrode formed in such a manner in which the reference electrode **42** is sandwiched by the top surface of the third substrate layer **3** and the first solid electrolyte layer **4**. As described above, the reference gas inlet layer **48** that communicates with the reference gas inlet space **43** is provided around the reference electrode **42**. As will be described later, it is possible to measure an oxygen concentration (oxygen partial pressure) in the first internal cavity **20**, an oxygen concentration (oxygen partial pressure) in the second internal cavity **40**, an

oxygen concentration (oxygen partial pressure) in the third internal cavity **61**, and an oxygen concentration (oxygen partial pressure) in the fourth internal cavity **63** by using the reference electrode **42**. The reference electrode **42** is formed as a porous cermet electrode (for example, a cermet electrode of Pt and Zro.sub.2).

[0036] In the measurement-object gas flow portion, the gas inlet port **10** is a portion that is open to an external space, and a measurement-object gas is taken into the sensor element **101** from the external space through the gas inlet port **10**. The first diffusion controlled portion **11** is a portion that applies predetermined diffusion resistance to a measurement-object gas taken in through the gas inlet port **10**. The buffer space **12** is a space provided to guide the measurement-object gas introduced from the first diffusion controlled portion **11** to the second diffusion controlled portion **13**. The second diffusion controlled portion **13** is a portion that applies predetermined diffusion resistance to the measurement-object gas introduced from the buffer space **12** into the first internal cavity **20**. When the measurement-object gas is introduced from the outside of the sensor element **101** into the first internal cavity **20**, the measurement-object gas rapidly taken into the sensor element **101** through the gas inlet port **10** due to pressure fluctuations of the measurement-object gas in the external space (due to pulsation of exhaust pressure when the measurement-object gas is the exhaust gas of an automobile) is not directly introduced into the first internal cavity **20** but, after pressure fluctuations of the measurement-object gas are cancelled out through the first diffusion controlled portion **11**, the buffer space **12**, and the second diffusion controlled portion **13**, the measurement-object gas is introduced into the first internal cavity **20**. With this configuration, pressure fluctuations of the measurement-object gas introduced into the first internal cavity **20** are almost ignorable. The first internal cavity **20** is provided as a space used to adjust an oxygen partial pressure in the measurement-object gas introduced through the second diffusion controlled portion **13**. The oxygen partial pressure is adjusted by the operation of a main pump cell **21**.

[0037] The main pump cell **21** is an electrochemical pump cell made up of an inner pump electrode **22** having a ceiling electrode portion **22***a* provided almost all over the under surface of the second solid electrolyte layer **6**, facing the first internal cavity **20**, the outer pump electrode **23** provided so as to be exposed to the external space in a region of the top surface of the second solid electrolyte layer **6**, corresponding to the ceiling electrode portion **22***a*, and the second solid electrolyte layer **6** sandwiched by these electrodes.

[0038] The inner pump electrode **22** is formed over the upper and lower solid electrolyte layers (the second solid electrolyte layer **6** and the first solid electrolyte layer **4**) defining the first internal cavity **20**, and the spacer layer **5** providing a side wall. Specifically, the ceiling electrode portion **22***a* is formed on the under surface of the second solid electrolyte layer **6**, providing a ceiling surface of the first internal cavity **20**, a bottom electrode portion **22***b* is formed on the top surface of the first solid electrolyte layer **4**, providing a bottom surface, a side electrode portion (not shown) is formed on the side wall surface (inner surface) of the spacer layer **5**, making both side wall portions of the first internal cavity **20**, so as to connect those ceiling electrode portion **22***a* and the bottom electrode portion **22***b*, and the inner pump electrode **22** is disposed with a structure in a tunnel form at a portion where the side electrode portion is disposed.

[0039] The inner pump electrode **22** and the outer pump electrode **23** each are formed as a porous cermet electrode (for example, a cermet electrode of Pt and Zro.sub.2, having an Au content of 1 percent). The inner pump electrode **22** that contacts with a measurement-object gas is formed by using a material of which the reduction ability for NOx components in the measurement-object gas is lowered.

[0040] By passing a pump current Ip**0** in a positive direction or a negative direction between the inner pump electrode **22** and the outer pump electrode **23** by applying a desired voltage Vp**0** between the inner pump electrode **22** and the outer pump electrode **23**, the main pump cell **21** is capable of pumping out oxygen in the first internal cavity **20** to the external space or pumping oxygen in the external space into the first internal cavity **20**.

[0041] In order to detect an oxygen concentration (oxygen partial pressure) in an atmosphere in the first internal cavity **20**, an electrochemical sensor cell, that is, a main pump control oxygen partial pressure detection sensor cell **80**, is made up of the inner pump electrode **22**, the second solid electrolyte layer **6**, the spacer layer **5**, the first solid electrolyte layer **4**, the third substrate layer **3**, and the reference electrode **42**.

[0042] An oxygen concentration (oxygen partial pressure) in the first internal cavity **20** is found by measuring an electromotive force (voltage V**0**) in the main pump control oxygen partial pressure detection sensor cell **80**. In addition, the pump current Ip**0** is controlled by executing feedback control over the voltage Vp**0** of a variable power supply **24** such that the voltage V**0** becomes a target value. With this configuration, it is possible to maintain the oxygen concentration in the first internal cavity **20** at a predetermined constant value.

[0043] The third diffusion controlled portion **30** is a portion that applies predetermined diffusion resistance to a measurement-object gas of which the oxygen concentration (oxygen partial pressure) is controlled by operation of the main pump cell **21** in the first internal cavity **20** to guide the measurement-object gas to the second internal cavity **40**.

[0044] The second internal cavity **40** is provided as a space used to further adjust the oxygen partial pressure by using an auxiliary pump cell **50** for the measurement-object gas adjusted in the oxygen concentration (oxygen partial pressure) in the first internal cavity **20** in advance and then introduced through the third diffusion controlled portion **30**. With this configuration, it is possible to highly accurately maintain the oxygen concentration in the second internal cavity **40** at a constant value, so it is possible to measure a highly accurate NOx concentration with the gas sensor **100**.

[0045] The auxiliary pump cell **50** is an auxiliary electrochemical pump cell made up of an auxiliary pump electrode **51** having a ceiling electrode portion **51***a* provided substantially all over the under surface of the second solid electrolyte layer **6**, facing the second internal cavity **40**, the outer pump electrode **23** (not limited to the outer pump electrode **23**, and an adequate electrode outside the sensor element **101** may be used), and the second solid electrolyte layer **6**.

[0046] The auxiliary pump electrode **51** is disposed in the second internal cavity **40** with a structure in a similar tunnel form to that of the inner pump electrode **22** provided in the above-described first internal cavity **20**. In other words, the auxiliary pump electrode **51** has such a structure in a tunnel form that a ceiling electrode portion **51***a* is formed on the second solid electrolyte layer **6** providing the ceiling surface of the second internal cavity **40**, a bottom electrode portion **51***b* is formed on the first solid electrolyte layer **4** providing the bottom surface of the second internal cavity **40**, a side electrode portion (not shown) that couples those ceiling electrode portion **51***a* and bottom electrode portion **51***b* is formed on each of both wall surfaces of the spacer layer **5**, providing a side wall of the second internal cavity **40**. The auxiliary pump electrode **51**, as well as the inner pump electrode **22**, is formed by using a material of which the reduction ability for NOx components in the measurement-object gas is lowered.

[0047] By applying a desired voltage Vp**1** between the auxiliary pump electrode **51** and the outer pump electrode **23**, the auxiliary pump cell **50** is capable of pumping out oxygen in an atmosphere in the second internal cavity **40** to the external space or pumping oxygen from the external space into the second internal cavity **40**.

[0048] In order to control an oxygen partial pressure in an atmosphere in the second internal cavity **40**, an electrochemical sensor cell, that is, an auxiliary pump control oxygen partial pressure detection sensor cell **81**, is made up of the auxiliary pump electrode **51**, the reference electrode **42**, the second solid electrolyte layer **6**, the spacer layer **5**, the first solid electrolyte layer **4**, and the third substrate layer **3**.

[0049] The auxiliary pump cell **50** performs pumping with a variable power supply **52** of which the voltage is controlled in accordance with an electromotive force (voltage V**1**) detected by the auxiliary pump control oxygen partial pressure detection sensor cell **81**. With this configuration, the

oxygen partial pressure in an atmosphere in the second internal cavity **40** is controlled to a low partial pressure that substantially does not influence measurement of NOx.

[0050] Together with this, its pump current Ip**1** is used to control the electromotive force of the main pump control oxygen partial pressure detection sensor cell **80**. Specifically, the pump current Ip**1** is input to the main pump control oxygen partial pressure detection sensor cell **80** as a control signal, and the gradient of the oxygen partial pressure in the measurement-object gas to be introduced from the third diffusion controlled portion **30** into the second internal cavity **40** is controlled to be constantly unchanged by controlling the above-described target value of the voltage V**0**. When used as a NOx sensor, the oxygen concentration in the second internal cavity **40** is maintained at a constant value of about 0.001 ppm by the functions of the main pump cell **21** and auxiliary pump cell **50**.

[0051] The fourth diffusion controlled portion **60** is a portion that applies predetermined diffusion resistance to measurement-object gas of which the oxygen concentration (oxygen partial pressure) is controlled by operation of the auxiliary pump cell **50** in the second internal cavity **40** to guide the measurement-object gas to the third internal cavity **61**. The fourth diffusion controlled portion **60** plays a role in limiting the amount of NOx flowing into the third internal cavity **61**.

[0052] The third internal cavity **61** is provided as a space used to perform a process related to measurement of a nitrogen oxide (NOx) concentration in a measurement-object gas on the measurement-object gas adjusted in oxygen concentration (oxygen partial pressure) in the second internal cavity **40** in advance and then introduced through the fourth diffusion controlled portion **60**. Measurement of a NOx concentration is mainly performed by operation of a first measurement pump cell **41** in the third internal cavity **61**.

[0053] The first measurement pump cell **41** measures a NOx concentration in the measurement-object gas in the third internal cavity **61**. The first measurement pump cell **41** is an electrochemical pump cell made up of a first measurement electrode **44** provided on the top surface of the first solid electrolyte layer **4**, facing the third internal cavity **61**, the outer pump electrode **23**, the second solid electrolyte layer **6**, the spacer layer **5**, and the first solid electrolyte layer **4**. The first measurement electrode **44** is a porous cermet electrode made of a material of which the reduction ability for NOx components in the measurement-object gas is raised as compared to the inner pump electrode **22**. The first measurement electrode **44** also functions as a NOx reduction catalyst that reduces NOx present in an atmosphere in the third internal cavity **61**.

[0054] The first measurement pump cell **41** is capable of pumping out oxygen produced as a result of decomposition of nitrogen oxides in an atmosphere around the first measurement electrode **44** and detecting the amount of oxygen produced as a pump current Ip**2**.

[0055] In order to detect an oxygen partial pressure around the first measurement electrode **44**, an electrochemical sensor cell, that is, a first measurement pump control oxygen partial pressure detection sensor cell **82**, is made up of the first solid electrolyte layer **4**, the third substrate layer **3**, the first measurement electrode **44**, and the reference electrode **42**. A variable power supply **46** is controlled in accordance with an electromotive force (voltage V**2**) detected by the first measurement pump control oxygen partial pressure detection sensor cell **82**.

[0056] A measurement-object gas guided into the second internal cavity **40** reaches the first measurement electrode **44** in the third internal cavity **61** through the fourth diffusion controlled portion **60** in a situation in which the oxygen partial pressure is controlled. Nitrogen oxides in the measurement-object gas around the first measurement electrode **44** are reduced (2NO.fwdarw.N.sub.2+O.sub.2) to produce oxygen. The produced oxygen is to be pumped by the first measurement pump cell **41**. At this time, the voltage Vp**2** of the variable power supply **46** is controlled such that the voltage V**2** detected by the first measurement pump control oxygen partial pressure detection sensor cell **82** is constant (target value). The amount of oxygen produced around the first measurement electrode **44** is proportional to the concentration of nitrogen oxides in the measurement-object gas, so a nitrogen oxide concentration in the measurement-object gas is

calculated by using the pump current Ip2 in the first measurement pump cell **41**.

[0057] When an oxygen partial pressure detection device is constructed as an electrochemical sensor cell by combining the first measurement electrode **44**, the first solid electrolyte layer **4**, the third substrate layer **3**, and the reference electrode **42**, an electromotive force according to the difference between the amount of oxygen produced by reduction of the NOx component in the atmosphere around the first measurement electrode **44**, and the amount of oxygen contained in the reference atmosphere can be detected, and accordingly, the concentration of the NOx component in the measurement-object gas can be determined.

[0058] The fifth diffusion controlled portion **62** is a portion that applies predetermined diffusion resistance to measurement-object gas in the third internal cavity **61** to guide the measurement-object gas to the fourth internal cavity **63**. The fifth diffusion controlled portion **62** plays a role in limiting the amount of carbon dioxide flowing into the fourth internal cavity **63**.

[0059] The fourth internal cavity **63** is provided as a space used to perform a process related to measurement of a carbon dioxide (CO.sub.2) concentration in a measurement-object gas which is introduced through the fifth diffusion controlled portion **62** after a nitrogen oxide is reduced in the third internal cavity **61**.

[0060] The second measurement pump cell **66** is an electrochemical pump cell made up of a second measurement electrode **67** provided on the top surface of the first solid electrolyte layer **4**, facing the fourth internal cavity **63**, the outer pump electrode **23**, the second solid electrolyte layer **6**, the spacer layer **5**, and the first solid electrolyte layer **4**. The second measurement electrode **67** is a porous cermet electrode made of a material of which the reduction ability for carbon dioxide components in the measurement-object gas is raised as compared to the inner pump electrode **22**. The second measurement electrode **67** also functions as a carbon dioxide reduction catalyst that reduces carbon dioxide present in an atmosphere in the fourth internal cavity **63**.

[0061] The second measurement pump cell **66** is capable of pumping out oxygen produced as a result of decomposition of carbon dioxide in an atmosphere around the second measurement electrode **67** and detecting the amount of oxygen produced as a pump current Ip3.

[0062] In order to detect an oxygen partial pressure around the second measurement electrode **67**, an electrochemical sensor cell, that is, a second measurement pump control oxygen partial pressure detection sensor cell **84**, is made up of the first solid electrolyte layer **4**, the third substrate layer **3**, the second measurement electrode **67**, and the reference electrode **42**. A variable power supply **68** is controlled in accordance with an electromotive force (voltage V3) detected by the second measurement pump control oxygen partial pressure detection sensor cell **84**.

[0063] A measurement-object gas in the third internal cavity **61** reaches the second measurement electrode **67** in the fourth internal cavity **63** through the fifth diffusion controlled portion **62** after NOx components in the measurement-object gas is reduced and the oxygen produced by the reduction is pumped by the first measurement pump cell **41**. Carbon dioxide in the measurement-object gas around the second measurement electrode **67** are reduced (2CO.sub.2.fwdarw.2CO+O.sub.2) to produce oxygen. The produced oxygen is to be pumped by the second measurement pump cell **66**. At this time, the voltage Vp3 of the variable power supply **68** is controlled such that the voltage V3 detected by the second measurement pump control oxygen partial pressure detection sensor cell **84** is constant (target value). The amount of oxygen produced around the second measurement electrode **67** is proportional to the concentration of carbon dioxide in the measurement-object gas, so a carbon dioxide concentration in the measurement-object gas is calculated by using the pump current Ip3 in the second measurement pump cell **66**.

[0064] An electrochemical sensor cell **83** is made up of the second solid electrolyte layer **6**, the spacer layer **5**, the first solid electrolyte layer **4**, the third substrate layer **3**, the outer pump electrode **23**, and the reference electrode **42**, and it is possible to detect an oxygen partial pressure in a measurement-object gas outside the sensor by using an electromotive force (voltage Vref) obtained by the sensor cell **83**.

[0065] In the gas sensor **100** having such a configuration, a measurement-object gas of which the oxygen partial pressure is maintained at a constantly unchanged low value (a value that substantially does not influence measurement of NOx) is supplied to the first measurement pump cell **41** by operating the main pump cell **21** and the auxiliary pump cell **50**. Therefore, it is possible to find a NOx concentration in the measurement-object gas in accordance with a pump current Ip**2** that flows as a result of pumping out oxygen, produced by reduction of NOx, by the first measurement pump cell **41** substantially in proportion to a NOx concentration in the measurement-object gas. It is possible to find a carbon dioxide concentration in the measurement-object gas in accordance with a pump current Ip**3** that flows as a result of pumping out oxygen, produced by reduction of carbon dioxide, by the second measurement pump cell **66**.

[0066] In addition, the sensor element **101** includes the heater portion **70** that plays a role in temperature adjustment for maintaining the temperature of the sensor element **101** by heating in order to increase the oxygen ion conductivity of the solid electrolyte. The heater portion **70** includes a heater connector electrode **71**, a heater **72**, a through-hole **73**, a heater insulating layer **74**, and a pressure release hole **75**.

[0067] The heater connector electrode **71** is an electrode formed in such a manner as to be in contact with the under surface of the first substrate layer **1**. Connection of the heater connector electrode **71** to an external power supply allows electric power to be supplied from the outside to the heater portion **70**. The heater **72** is an electric resistor formed in such a manner as to be sandwiched by the second substrate layer **2** and the third substrate layer **3** from upper and lower sides. The heater **72** is connected to the heater connector electrode **71** via the through-hole **73**, and is supplied with electric power from a heater power supply **76** (see FIG. **2**) to generate heat to increase and retain the temperature of the solid electrolyte forming the sensor element **101**.

[0068] The heater **72** is embedded all over the region from the first internal cavity **20** to the fourth internal cavity **63**, and is capable of adjusting the overall sensor element **101** to a temperature at which the solid electrolyte is activated.

[0069] The heater insulating layer **74** is an electrically insulating layer formed of an insulating material, such as alumina, on the top and under surfaces of the heater **72**. The heater insulating layer **74** is formed for the purpose of obtaining an electrical insulation property between the second substrate layer **2** and the heater **72** and an electrical insulation property between the third substrate layer **3** and the heater **72**.

[0070] The pressure release hole **75** is a portion provided so as to extend through the third substrate layer **3** and the reference gas inlet layer **48** and communicate with the reference gas inlet space **43**. The pressure release hole **75** is formed for the purpose of easing an increase in internal pressure resulting from an increase in temperature in the heater insulating layer **74**.

[0071] As shown in FIG. **2**, the control apparatus **95** includes the above-mentioned variable power supplies **24**, **46**, **52**, **68**, the above-mentioned heater power supply **76**, and a controller **96**. The controller **96** is a microprocessor including a CPU **97**, and a storage section **98**. The storage section **98** is a non-volatile memory capable of rewriting information, and can store various programs and various data, for example. The controller **96** receives input of voltage V**0** detected by the main pump control oxygen partial pressure detection sensor cell **80**, voltage V**1** detected by the auxiliary pump control oxygen partial pressure detection sensor cell **81**, voltage V**2** detected by the first measurement pump control oxygen partial pressure detection sensor cell **82**, voltage V**3** detected by the second measurement pump control oxygen partial pressure detection sensor cell **84**, voltage Vref detected by the sensor cell **83**, pump current Ip**0** detected by the main pump cell **21**, pump current Ip**1** detected by the auxiliary pump cell **50**, pump current Ip**2** detected by the first measurement pump cell **41**, and pump current Ip**3** detected by the second measurement pump cell **66**. The controller **96** controls the voltages Vp**0**, Vp**1**, Vp**2**, Vp**3** output by the variable power supplies **24**, **46**, **52**, **68** by outputting a control signal to the variable power supplies **24**, **46**, **52**, **68**, thereby controlling the main pump cell **21**, the auxiliary pump cell **50**, the first measurement pump

cell **41** and the second measurement pump cell **66**. The controller **96** controls the electric power supplied to the heater **72** from the heater power supply **76** by outputting a control signal to the heater power supply **76**. The storage section **98** also stores the later-described target values V**0***, V**1***, V**2***, V**3***, etc. The CPU **97** of the controller **96** controls the cells **21**, **41**, **50**, **60** by referring to these target values V**0***, V**1***, V**2***, V**3***.

[0072] The controller **96** executes an auxiliary pump control process of controlling the auxiliary pump cell **50** so that the oxygen concentration in the second internal cavity **40** reaches a target concentration. Specifically, the controller **96** controls the auxiliary pump cell **50** by executing feedback control on the voltage Vp**1** of the variable power supply **52** so that the voltage V**1** reaches a constant value (referred to as target value V**1***). The target value V**1*** is defined as the value that causes the oxygen concentration in the second internal cavity **40** to reach a predetermined low oxygen concentration that does not substantially affect measurement of NOx.

[0073] The controller **96** executes a main pump control process of controlling the main pump cell **21** so that the pump current Ip**1** flowing when the oxygen concentration in the second internal cavity **40** is adjusted by the auxiliary pump cell **50** in the auxiliary pump control process reaches a target current (referred to as target value Ip**1***). Specifically, the controller **96** sets (feedback-controls) a target value (referred to as a target value V**0***) of the voltage V**0** based on the pump current Ip**1** so that the pump current Ip**1** caused to flow by the voltage Vp**1** reaches the constant target current Ip**1***. The controller **96** then performs feedback control on the voltage Vp**0** of the variable power supply **24** so that the voltage V**0** reaches the target value V**0*** (in other words, the oxygen concentration in the first internal cavity **20** reaches the target concentration). The gradient of oxygen partial pressure in the measurement-object gas to be introduced from the third diffusion controlled portion **30** into the second internal cavity **40** is made unchanged constantly by the main pump control process. The target value V**0*** is set to a value which causes the oxygen concentration in the first internal cavity **20** to be higher than 0% and reach a low oxygen concentration. The pump current Ip**0** which flows during the main pump control process varies according to the oxygen concentration in the measurement-object gas (that is, the measurement-object gas in the vicinity of the sensor element **101**) which flows into the measurement-object gas flow portion through the gas inlet port **10**. Thus, the controller **96** can also detect the oxygen concentration in the measurement-object gas based on the pump current Ip**0**.

[0074] The main pump control process and the auxiliary pump control process described above are also collectively referred as an adjustment pump control process. The first internal cavity **20** and the second internal cavity **40** are also collectively referred as an oxygen concentration adjustment chamber. The main pump cell **21** and the auxiliary pump cell **50** are also collectively referred as an adjustment pump cell. The controller **96** executes the adjustment pump control process, thus the adjustment pump cell adjusts the oxygen concentration in the oxygen concentration adjustment chamber.

[0075] In addition, the controller **96** executes a first measurement pump control process of controlling the first measurement pump cell **41** so that the voltage V**2** reaches a constant value (referred to as a target value V**2***) (in other words, so that the oxygen concentration in the third internal cavity **61** reaches a predetermined low concentration). Specifically, the controller **96** controls the first measurement pump cell **41** by performing feedback control on the voltage Vp**2** of the variable power supply **46** so that the voltage V**2** reaches the target value V**2***. Oxygen is pumped out from the third internal cavity **61** by the first measurement pump control process.

[0076] Execution of the first measurement pump control process causes oxygen to be pumped out from the third internal cavity **61** so that the oxygen produced due to reduction of NOx in the measurement-object gas in the third internal cavity **61** become substantially zero. The controller **96** obtains a pump current Ip**2** as a detected value corresponding to the oxygen produced in the third internal cavity **61** from NOx, and calculates the NOx concentration in the measurement-object gas based on the pump current Ip**2**.

[0077] The storage section **98** stores a relational expression (for example, an expression of a linear function or a quadratic function) or a map as a correspondence relationship between the pump current Ip**2** and the NOx concentration. Such a relational expression or map can be determined in advance by an experiment.

[0078] In addition, the controller **96** executes a second measurement target pump control process of controlling the second measurement pump cell **66** so that the voltage V**3** reaches a constant value (referred to as a target value V**3***) (in other words, so that the oxygen concentration in the fourth internal cavity **63** reaches a predetermined low concentration). Specifically, the controller **96** controls the second measurement pump cell **66** by performing feedback control on the voltage Vp**3** of the variable power supply **68** so that the voltage V**3** reaches the target value V**3***. Oxygen is pumped out from the fourth internal cavity **63** by the second measurement pump control process.

[0079] Execution of the second measurement pump control process causes oxygen to be pumped out from the fourth internal cavity **63** so that the oxygen produced due to reduction of carbon dioxide in the measurement-object gas in the fourth internal cavity **63** become substantially zero. The controller **96** obtains a pump current Ip**3** as a detected value corresponding to the oxygen produced in the fourth internal cavity **63** from carbon dioxide, and calculates the carbon dioxide concentration in the measurement-object gas based on the pump current Ip**3**.

[0080] The controller **96** performs a heater control process of controlling the heater **72** by outputting a control signal to the heater power supply **76** so that the temperature of the heater **72** reaches a target temperature (for example, 800° C.). Here, the temperature of the heater **72** can be expressed as a linear function of the resistance value of the heater **72**. Thus, in the heater control process, the controller **96** calculates the resistance value of the heater **72** as a value (a value convertible to the temperature) regarded as the temperature of the heater **72**, and performs feedback control on the heater power supply **76** so that the calculated resistance value reaches a target resistance value (a resistance value corresponding to the target temperature). The controller **96** obtains, for example, the voltage of the heater **72** and the current flowing through the heater **72**, and can calculate the resistance value of the heater **72** based on the obtained voltage and current. The controller **96** may calculate the resistance value of the heater **72**, for example, by 3-terminal method or 4-terminal method. When passing an electric current through the heater **72**, the heater power supply **76** adjusts the electric power supplied to the heater **72** by changing the value of the voltage to be applied to the heater **72** based on, for example, a control signal from the controller **96**.

[0081] The inventors have studied the relationship between the target value V**1*** of the gas sensor **100**, the water concentration in the measurement-object gas, and the pump current Ip**2**. First, as the measurement-object gas, three gas types were prepared: a first gas containing nitrogen as the base gas, an oxygen concentration of 0%, a water concentration of 38, an NO concentration of 0 ppm, and an carbon dioxide concentration of 0%, a second gas having the same composition as that of the first gas except for a water concentration of 9%, and a third gas having the same composition as that of the first gas except for a water concentration of 15%. Next, the target value V**2*** was set to 400 mV, the target value V**1*** was set to 300 mV, and the pump current Ip**2** was measured when the controller **96** performed the above-described adjustment pump control process and first measurement pump control process on the first gas. The controller **96** started the above-described heater control process, then after the temperature of the heater **72** reached near the target temperature, started the adjustment pump control process and the first measurement pump control process, and subsequently measured the value of the pump current Ip**2** with the pump current Ip**2** stable. Furthermore, the controller **96** measured the pump current Ip**2** corresponding to the value of each target value V**1*** in the same manner as described above except that the target value V**1*** is changed to 350 mV, 400 mV, 450 mV. For the second gas and the third gas, the controller **96** measured the pump current Ip**2** corresponding to the value of each target value V**1*** in the same manner as described above. The result is shown in FIG. **3**. FIG. **3** is a graph showing a relationship between target value V**1***, water concentration in the measurement-object gas, and pump current

Ip**2**. The pump current Ip**2** in the vertical axis of FIG. **3** is shown as a value (unit is ppm) obtained by converting the pump current Ip**2** to an NO concentration using a correspondence relationship between the pump current Ip**2** and the NOx concentration stored in the storage section **98**. Since each of the first to third gases has an NO concentration of 0 ppm, the pump current Ip**2** is theoretically 0 μA in each case, but actually, a slight pump current Ip**2** flows. Such a pump current Ip**2** which is caused to flow due to a factor other than NOx is referred to as an offset current Ip**2**offset. Thus, FIG. **3** shows a relationship between the target value V**1***, the water concentration in the measurement-object gas, and the offset current Ip**2**offset. The offset current is also contained in the pump current Ip**2** when the NOx concentration is not 0 ppm.

[0082] As shown in FIG. **3**, there is a linear correlation between the target value V**1*** and the offset current Ip**2**offset, and it has been identified that the offset current Ip**2**offset tends to decrease for higher target value V**1***. Also, regarding the slope of the change in the offset current Ip**2**offset for the change in the target value V**1***, it has been identified that the absolute value of the slope tends to increase for higher water concentration in the measurement-object gas. FIG. **4** is a graph showing a relationship between the water concentration in the measurement-object gas and the slope of the change in the offset current Ip**2**offset for the change in the target value V**1***, the relationship being calculated from the data shown in FIG. **3**. As shown in FIG. **4**, there is a linear correlation between the water concentration and the slope of the offset current Ip**2**offset, and it has been identified that the slope of the offset current Ip**2**offset tends to decrease (the absolute value of negative slope tends to increase) for higher water concentration. From these results, it is found that the water concentration in the measurement-object gas can be detected based on the change (for example, the slope of the change in the offset current Ip**2**offset when the target value V**1*** is changed) in the pump current Ip**2** when the target value V**1*** is changed. This is new knowledge obtained by the inventors this time.

[0083] As in FIG. **3**, the inventors have studied the relationship between the target value V**2*** of the gas sensor **100**, the water concentration in the measurement-object gas, and the pump current Ip**2**. Specifically, with the target value V**1*** set to 385 mV, and the target value V**2*** changed in four ways: 300 mV, 350 mV, 400 mV, 450 mV, using the same first to third gases as mentioned above, a pump current Ip**2** corresponding to the value of each target value V**2*** was measured in the same manner as in the measurement of data in FIG. **3**. The result is shown in FIG. **5**. FIG. **5** is a graph showing a relationship between the target value V**2***, the water concentration in the measurement-object gas and the pump current Ip**2**. FIG. **6** is a graph showing a relationship between the water concentration in the measurement-object gas and the slope of the change in the offset current Ip**2**offset for the change in the target value V**2***, the relationship being calculated from the data shown in FIG. **5**.

[0084] As shown in FIG. **5**, there is a linear correlation between the target value V**2*** and the offset current Ip**2**offset, and it has been identified that the offset current Ip**2**offset tends to increase for higher target value V**2***. Also, regarding the slope of the change in the offset current Ip**2**offset for the change in the target value V**2***, it has been identified that the absolute value of the slope tends to increase for higher water concentration in the measurement-object gas. As shown in FIG. **6**, there is a linear correlation between the water concentration and the slope of the offset current Ip**2**offset, and it has been identified that the slope of the offset current Ip**2**offset tends to increase (the absolute value of positive slope tends to increase) for higher water concentration. From these results, it is found that the water concentration in the measurement-object gas can be detected based on the change (for example, the slope of the change in the offset current Ip**2**offset when the target value V**2*** is changed) in the pump current Ip**2** when the target value V**2*** is changed. This is new knowledge obtained by the inventors this time.

[0085] Based upon the foregoing, when at least one of the target value V**1*** or the target value V**2*** is changed, change in the pump current Ip**2** which flows during execution of the adjustment pump control process and the first measurement pump control process correlates with the water

concentration in the measurement-object gas, thus it is found that the water concentration can be detected based on the change in the pump current Ip2. In the present embodiment, as a relationship between the slope of the change in the pump current Ip2 and the water concentration in the measurement-object gas when the target value V1* is changed, a linear function or a map representing the linear relationship shown in FIG. **4** is stored in the storage section **98**.

[0086] Note that the reason why the relationship shown in FIG. **3** to FIG. **6** holds between the target value V1* and the target value V2*, the water concentration in the measurement-object gas, and the pump current Ip2 (particularly, the offset current Ip2offset) is as follows.

[0087] First, the relationship between the water in the measurement-object gas and the offset current Ip2offset will be described. When the adjustment pump control process (herein, the main pump control process and the auxiliary pump control process) is performed with water present in the measurement-object gas, at least part of the water around the auxiliary pump electrode **51** is decomposed by the voltage Vp1 of the variable power supply **52**, and hydrogen (H2) and oxygen (O2) are produced. The produced oxygen is pumped out from the periphery of the auxiliary pump electrode **51**, that is, from the second internal cavity **40** by the auxiliary pump cell **50**, and at least part of the produced hydrogen reaches the third internal cavity **61**. The hydrogen which has reached the third internal cavity **61** reacts with the oxygen in the third internal cavity **61** to produce water, thus a decrease occurs in the amount of oxygen pumped out from the third internal cavity **61** by the first measurement pump control process, in other words, the pump current Ip2 decreases. In contrast, when the first measurement pump control process is performed with water present in the measurement-object gas, at least part of the water around the first measurement electrode **44** in the third internal cavity **61** is decomposed by the voltage Vp2 of the variable power supply **46**, and hydrogen (H2) and oxygen (O2) are produced. Thus, an increase occurs in the amount of oxygen pumped out from the third internal cavity **61** by the first measurement pump control process, in other words, the pump current Ip2 increases. In this manner, the pump current Ip2 decreases due to the hydrogen produced from the water around the auxiliary pump electrode **51**, and the pump current Ip2 increases due to the oxygen produced from water around the first measurement electrode **44**, thus the sum of the amount of decrease and the amount of increase in the pump current Ip2 not from NOx in the measurement-object gas is observed as the offset current Ip2offset.

[0088] For higher target value V1*, in other words, for lower target value of the oxygen concentration in the second internal cavity **40**, the voltage Vp1 is more likely to have a high value due to the auxiliary pump control process, thus an increase occurs in the amount of hydrogen produced from decomposition of water around the auxiliary pump electrode **51** by the voltage Vp1, and the amount of decrease in the pump current Ip2 also increases. In addition, for higher water concentration in the measurement-object gas, an increase occurs in the amount of hydrogen produced from decomposition of water around the auxiliary pump electrode **51**, thus the amount of decrease in the pump current Ip2 according to the amount of change in the target value V1*, in other words, the slope of the change in the pump current Ip2 for the change in the target value V1* becomes steeper. In other words, the absolute value of the slope increases. For these reasons, the relationship shown in FIG. **3** and FIG. **4** is probably exhibited.

[0089] Similarly, for higher target value V2*, in other words, for lower target value of the oxygen concentration in the third internal cavity **61**, the voltage Vp2 is more likely to have a high value due to the first measurement pump control process, thus an increase occurs in the amount of oxygen produced from decomposition of water due to the voltage Vp2 around the first measurement electrode **44**, and the amount of increase in the pump current Ip2 also increases. In addition, for higher water concentration in the measurement-object gas, an increase occurs in the amount of oxygen produced from decomposition of water around the first measurement electrode **44**, thus the amount of increase in the pump current Ip2 according to the amount of change in the target value V2*, in other words, the slope of the change in the pump current Ip2 for the change in the target value V2* becomes steeper. In other words, the absolute value of the slope increases. For

these reasons, the relationship shown in FIG. **5** and FIG. **6** is probably exhibited.

[0090] Next, an example of the process of making measurement of the specific gas concentration (NOx concentration, carbon dioxide concentration, water concentration, and oxygen concentration in this case) by the controller **96** of the gas sensor **100** will be described. FIG. **7** is a flowchart showing an example of a control routine performed by the controller **96**. The controller **96** stores the routine, for example, in the storage section **98**. Upon input of a start command, for example, from an engine ECU which is not shown, the controller **96** starts the control routine.

[0091] Upon start of the control routine, the CPU **97** of the controller **96** first starts the above-described heater control process (step S**100**). Subsequently, the CPU **97** starts the above-described adjustment pump control process, first measurement pump control process, and second measurement pump control process (step S**110**). At this point, as the values used for measurement of NOx concentration, the values pre-stored in the storage section **98** are used as the target value V**1*** and the target value V**2***. Next, the CPU**97** determines whether or not a concentration derivation timing for deriving the concentration of the specific gas has been reached (step S**120**). For example, at every elapse of a predetermined time or when a concentration derivation command is input from the engine ECU, the CPU **97** determines that a concentration derivation timing has been reached.

[0092] When it is determined in step S**120** that a concentration derivation timing has been reached, the CPU **97** first performs a oxygen concentration detection process of deriving the oxygen concentration based on the pump current Ip**0** (step S**125**). The CPU **97** controls the main pump cell **21** so that the voltage V**0** reaches the target value V**0*** (in other words, the oxygen concentration in the first internal cavity **20** reaches the target concentration) in the adjustment pump control process (particularly, the main pump control process in this case), thus the CPU **97** can derive the oxygen concentration in the measurement-object gas based on the pump current Ip**0** as described above. In the present embodiment, a relational expression or a map representing a correspondence relationship between the pump current Ip**0** and the oxygen concentration is obtained through experiments and is preliminarily stored in the storage section **98**. In step S**125**, the CPU **97** calculates the oxygen concentration in the measurement-object gas based on the current pump current Ip**0** and the correspondence relationship stored in the storage section **98**.

[0093] Subsequently, the CPU **97** performs a water concentration detection process of detecting the water concentration in the measurement-object gas based on the change in the pump current Ip**2** which flows during execution of the adjustment pump control process and the first measurement pump control process when at least one of the target value V**1*** or the target value V**2*** is changed (steps S**130**, S**140**). In the present embodiment, in the water concentration detection process, the CPU **97** changes the target value V**1***, and does not change the target value V**2***. In the water concentration detection process, the CPU **97** first calculates the slope G of the change in the pump current Ip**2** when the target value V**1*** is changed (step S**130**). Specifically, the CPU **97** first measures the current pump current Ip**2**, and obtains it as the value of the pump current Ip**2** in a state before the target value V**1*** is changed. Next, the CPU **97** changes the target value V**1***, waits until the value of the pump current Ip**2** becomes stable, measures the pump current Ip**2** after becoming stable, and obtains it as the value of the pump current Ip**2** in a state after the change. The slope G is derived by dividing the difference between the values of the pump current Ip**2** before and after the change by the difference between the values of the target value V**1*** before and after the change. Note that the length of time since the target value V**1*** is changed until the pump current Ip**2** becomes stable is an extremely short time (from several msec to several tens of msec), and normally, almost no change occurs during this time in the NOx concentration in the exhaust gas of an internal combustion engine. Thus, the difference between the values of the pump current Ip**2** before and after the change in the target value V**1*** can be regarded as the amount of change in the offset current Ip**2**offset before and after the change in the target value V**1***. Therefore, the slope G derived in step S**130** corresponds to the slope of the straight line shown in FIG. **3** and the value of

the vertical axis in FIG. **4**. The CPU **97** then calculates the water concentration in the measurement-object gas based on the derived slope G and the correspondence relationship (the above-mentioned correspondence relationship between the slope of the change in the pump current Ip**2** and the water concentration in the measurement-object gas when the target value V**1*** is changed) stored in the storage section **98** (step S**140**). In step S**130**, the target value V**1*** may be changed so that the absolute value thereof is increased, or so that the absolute value is decreased. However, each of the values before and after the change is preferably less than or equal to the absolute value of the target value V**1*** defined for measurement of the NOx concentration. For example, when the target value V**1*** before the change is the same as the target value V**1*** defined for measurement of the NOx concentration, it is preferable that the target value V**1*** be changed so that the absolute value thereof is decreased. In this manner, decomposition of NOx due to too high voltage Vp**1** around the auxiliary pump electrode **51** can be prevented, thus reduction in the accuracy of measurement of the NOx concentration can be prevented.

[0094] When deriving the water concentration in step S**140**, the CPU **97** returns the target value V**1*** to the value before the change. Specifically, the CPU **97** returns the target value V**1*** to the value defined for measurement of the NOx concentration (step S**150**). Subsequently, the CPU **97** obtains the pump current Ip**2** which is caused to flow by the first measurement pump control process (step S**160**), and derives the NOx concentration in the measurement-object gas based on the obtained pump current Ip**2** and the correspondence relationship (the above-mentioned correspondence relationship between the pump current Ip**2** and the NOx concentration) stored in the storage section **98** (step S**170**). The CPU **97** then corrects the NOx concentration derived in step S**170** based on the water concentration derived in step S**140**, and derives the NOx concentration after the correction (step S**180**). As shown in FIG. **3**, the offset current Ip**2**offset of the pump current Ip**2** changes due to the water concentration in the measurement-object gas. Thus, even with the same NOx concentration in the measurement-object gas, the pump current Ip**2** may be changed according to the water concentration in the measurement-object gas, and an error may occur in the derived NOx concentration. Thus, in the present embodiment, the CPU **97** corrects the NOx concentration according to the pump current Ip**2** based on the detected water concentration. For example, when the target value V**1*** is 350 mV in FIG. **3**, the offset current Ip**2**offset for the water concentration of 15% is greater than the offset current Ip**2**offset for the water concentration of 3% by 3 ppm in NOx concentration conversion. Thus, for example, when the correspondence relationship between the pump current Ip**2** and the NOx concentration, stored in the storage section **98** is calculated using the measurement-object gas with a water concentration of 3%, the derived NOx concentration with an actual water concentration in the measurement-object gas of 15% is calculated as the value greater than the true concentration by 3 ppm. Thus, when the water concentration derived in step S**140** is 15%, as the NOX concentration after correction, the CPU **97** derives, the value obtained by subtracting 3 ppm as a correction amount from the NOx concentration [ppm] derived in step S**170**. In this manner, a change in the offset current Ip**2**offset due to a difference in water concentration can be canceled, and the NOx concentration after correction has a value closer to the true concentration. Such a correspondence relationship between the water concentration and the correction amount to NOx concentration can be determined in advance by an experiment or the like, and stored in the storage section **98**. In step S**180**, the CPU **97** derives a correction amount based on the water concentration and the correspondence relationship, and calculates the NOx concentration after the correction. Note that instead of deriving a correction amount, a correspondence relationship between the NOx concentration and the NOx concentration after correction based on the water concentration and the pump current Ip**2** may be stored in the storage section **98**, and the NOx concentration after correction may be derived based on the correspondence relationship. Alternatively, the CPU **97** may correct the pump current Ip**2** derived in step S**170** based on the water concentration, and may derive the NOx concentration based on the pump current Ip**2** after correction. These methods also apply correction to the NOx

concentration based on the water concentration.

[0095] When deriving the NOx concentration in step S**180**, the CPU **97** performs a carbon dioxide concentration detection process of detecting the carbon dioxide concentration in the measurement-object gas (steps S**190**, S**200**). Specifically, first, the CPU **97** obtains the pump current Ip**3** which is caused to flow by the second measurement pump control process (step S**190**), and derives the carbon dioxide concentration in the measurement-object gas based on the obtained pump current Ip**3** and the water concentration derived in step S**140** (step S**200**). Here, the CPU **97** control the second measurement pump cell **66** so that the voltage V**3** reaches the target value V**3*** (in other words, the oxygen concentration in the fourth internal cavity **63** reaches the target concentration) in the second measurement pump control process in advance. Thus, the pump current Ip**3** that flows in the second measurement pump cell **66** correlates with the amount of oxygen produced in the fourth internal cavity **63** from carbon dioxide. However, if the measurement-object gas contains water, not only carbon dioxide but also water is reduced in the fourth internal cavity **63**. Thus, the pump current Ip**3** which is caused to flow by the second measurement pump control process is a value based on the carbon dioxide concentration and the water concentration. Thus, in the present embodiment, the CPU **97** derives the carbon dioxide concentration based on the pump current Ip**3** and the water concentration. For example, there is a linear correlative relationship between a total value Cs [%] of the water concentration and the carbon dioxide concentration in the measurement-object gas and the pump current Ip**3**, as shown in FIG. **8**. In the present embodiment, a relational expression or a map, for example, representing a correspondence relationship between the pump current Ip**3** and the total value Cs is obtained through experiments and is preliminarily stored in the storage section **98**. The CPU **97** derives the total value Cs based on the current pump current Ip**3** and the correspondence relationship stored in the storage section **98** in step S**200**, and describes a value obtained by subtracting the water concentration derived in step S**140** from the total value Cs, as the carbon dioxide concentration in the measurement-object gas. Thus, the pump current Ip**3** is affected by both the water concentration and the carbon dioxide concentration. However, the inventors have found that the water concentration in the measurement-object gas correlates with the change in the pump current Ip**2** when at least one of the target value V**1*** or the target value V**2*** is changed. Thus, it was newly found that the carbon dioxide concentration can be accurately derived from the pump current Ip**3** using this. In addition, almost all of NOx in the measurement-object gas is reduced in the third internal cavity **61** provided upstream of the fourth internal cavity **63**, and almost all of the oxygen produced by the reduction is pumped out by the first measurement pump cell **41**, so the NOx concentration in the measurement-object gas has almost no effect on the pump current Ip**3**.

[0096] The total value Cs can also be expressed as "a carbon dioxide concentration based on pump current Ip**3** when the water concentration is assumed to be 0%". Therefore, the process in step S**200**, which subtracts the water concentration from the total value Cs derived based on the pump current Ip**3**, can also be referred to as the process of correcting the carbon dioxide concentration derived based on the pump current Ip**3** with the water concentration derived in step S**140**.

[0097] After step S**200**, or when a concentration derivation timing has not been reached in step S**120**, the CPU **97** executes the processes in and after S**120**. The CPU **97** repeatedly measures the NOx concentration, the carbon dioxide concentration, the water concentration, and the oxygen concentration in the measurement-object gas by executing the control routine as described above. The CPU **97** outputs these derived values to the engine ECU, and stores these derived values in the storage section **98**.

[0098] The correspondence relationships between the components in the present embodiment and the components in the present invention will now be clarified. The layered body obtained by layering six layers consisting of the first substrate layer **1**, the second substrate layer **2**, the third substrate layer **3**, the first solid electrolyte layer **4**, the spacer layer **5** and the second solid electrolyte layer **6** in that order corresponds to the element body according to the present invention,

the third internal cavity **61** corresponds to the first measurement chamber, the first measurement electrode **44** corresponds to the first inner measurement electrode, the fourth internal cavity **63** corresponds to the second measurement chamber, the second measurement electrode **67** corresponds to the second inner measurement electrode, the inner pump electrode **22** and the auxiliary pump electrode **51** correspond to the inner adjustment electrode, the voltage V**1** corresponds to the adjustment voltage, the target value V**1*** corresponds to the adjustment voltage target value, the voltage V**2** corresponds to the first measurement voltage, the target value V**2*** corresponds to the first measurement voltage target value, the pump current Ip**2** corresponds to the first measurement pump current, the voltage V**3** corresponds to the second measurement voltage, the target value V**3*** corresponds to the second measurement voltage target value, and the pump current Ip**3** corresponds to the second measurement pump current. In addition, the pump current Ip**0** corresponds to the adjustment pump current, the inner pump electrode **22** corresponds to the inner main pump electrode, and the auxiliary pump electrode **51** corresponds to the inner auxiliary pump electrode.

[0099] With the gas sensor **100** in the present embodiment described in detail above, the control apparatus **95** detects the NOx concentration in the measurement-object gas based on the pump current Ip**2** which is caused to flow through the first measurement pump cell **41** by the first measurement pump control process. The control apparatus **95** detects the carbon dioxide concentration in the measurement-object gas based on the pump current Ip**3** that flows in the second measurement pump cell **66** by the second measurement pump control process and the water concentration in the measurement-object gas (the value based on the change in the pump current Ip**2** which flows during execution of the adjustment pump control process and the first measurement pump control process when at least one of the target value V**1*** or the target value V**2*** is changed). Thus, the gas sensor **100** in the present embodiment can detect the NOx concentration and the carbon dioxide concentration in the measurement-object gas.

[0100] The control apparatus **95** detects the water concentration in the measurement-object gas based on the change in the pump current Ip**2** which flows during execution of the adjustment pump control process and the first measurement pump control process when at least one of the target value V**1*** or the target value V**2*** is changed. Therefore, the gas sensor **100** can detect the water concentration in addition to the NOx concentration and the carbon dioxide concentration in the measurement-object gas. Furthermore, the control apparatus **95** derives the total value of the carbon dioxide concentration and the water concentration in the measurement-object gas based on the pump current Ip**3**, and detects the carbon dioxide concentration in the measurement-object gas by subtracting the water concentration detected in step S**140** from the total value derived. In this manner, the control apparatus **95** can detect the carbon dioxide concentration using a relatively simple method.

[0101] The control apparatus **95** detects the oxygen concentration in the measurement-object gas based on the pump current Ip**0** which is caused to flow by the main pump control process that is a part of the adjustment pump control process. In this manner, the gas sensor **100** can detect the oxygen concentration in the measurement-object gas in addition to the NOx concentration and the carbon dioxide concentration in the measurement-object gas.

[0102] Note that the present invention is not limited to the above-described embodiment at all, and may be, of course, implemented in various modes within the technical scope of the present invention.

[0103] For example, in the above-described embodiment, in step S**130** of the control routine of FIG. **7**, the CPU **97** derives the water concentration based on the slope G of the change in the pump current Ip**2** when the target value V**1*** is changed; however, the CPU **97** may derive the water concentration based on the change in the pump current Ip**2** instead of the slope G when the target value V**1*** is changed. For example, the water concentration may be derived based on the amount of change or rate of change in the pump current Ip**2** before and after the change in the target value

V1*. In this case, a correspondence relationship between the amount of change or rate of change in the pump current Ip2 and the water concentration may be pre-stored in the storage section 98.

[0104] In the above-described embodiment, in step S130 of the control routine of FIG. 7, the CPU 97 derives the water concentration based on the slope G of the change in the pump current Ip2 when the target value V1* is changed; however, the CPU 97 may derive the water concentration based on the change in the pump current Ip2 when the target value V2* is changed. For example, the CPU 97 may derive the slope (corresponding to the slope of the straight line shown in FIG. 5 and the value of the vertical axis in FIG. 6) of the change in the pump current Ip2 when the target value V2* is changed without changing the value V1*, and may derive the water concentration based on the derived slope. In this case, a correspondence relationship (corresponding to the linear correspondence relationship shown in FIG. 6) between the slope of the change in the pump current Ip2 and the water concentration when the target value V2* is changed may be pre-stored in the storage section 98. Note that when the target value V2* is changed, the target value V2* may be changed so that the absolute value thereof is increased, or so that the absolute value is decreased. However, each of the values before and after the change is preferably greater than or equal to the target value V2* defined for measurement of the NOx concentration. For example, when the target value V2* before the change is the same as the target value V2* defined for measurement of the NOx concentration, it is preferable that the target value V2* be changed so that the absolute value thereof is increased. In this manner, prevention of the pump current Ip2 from reaching the limiting current due to too low voltage Vp2 can be avoided, thus reduction in the accuracy of measurement of the NOx concentration can be prevented.

[0105] In the water concentration detection process, the CPU 97 may derive the water concentration based on the pump current Ip2 when both the target value V1* and the target value V2* are changed. In this case, it is preferable that the direction of change in the pump current Ip2 due to change in the target value V1* be the same as the direction of change in the pump current Ip2 due to change in the target value V2*. For example, when the absolute value of the target value V1* is changed to a smaller value and the absolute value of the target value V2* is changed to a larger value, these changes each causes the pump current Ip2 to increase. Alternatively, when the absolute value of the target value V1* is changed to a larger value and the absolute value of the target value V2* is changed to a smaller value, these changes each causes the pump current Ip2 to decrease. When the target value V1* and the target value V2* are changed by one of these methods, even with a small amount of change in each of the target value V1* and the target value V2*, the change in the pump current Ip2 caused by the water in the measurement-object gas is relatively large. Therefore, the water concentration is easily detected based on the change in the pump current Ip2. Note that when both the target value V1* and the target value V2* are changed, the CPU 97 may calculate, for example, the amount of change or rate of change in the pump current Ip2 instead of the slope of the pump current Ip2, and may derive the water concentration based on the amount of change or rate of change.

[0106] For example, in the above embodiment, the CPU 97 derives the carbon dioxide concentration based on the water concentration derived in step S140 and the pump current Ip3, but the configuration is not limited thereto. Even if the CPU 97 does not derive the water concentration itself, the CPU 97 can derive the carbon dioxide concentration based on the change in the pump current Ip2 which flows during execution of the adjustment pump control process and the first measurement pump control process when at least one of the target value V1* or the target value V2* is changed and the pump current Ip3. For example, the slope G derived in step S130 may be used as a value representing the change in the pump current Ip2, or the amount or rate of change in the pump current Ip2 may be used. For example, if the slope G is used, a correspondence relationship between the slope G, the pump current Ip3 and the carbon dioxide concentration may be obtained through experiments and be preliminarily stored in the storage section 98. FIG. 9 is a graph showing one example of this correspondence relationship. As illustrated in FIG. 9, this

correspondence relationship is such that the greater the absolute value of the slope G (i.e., the greater the water concentration), the lower the carbon dioxide concentration tends to be, and the greater the pump current Ip**3**, the higher the carbon dioxide concentration tends to be. In FIG. **9**, for example, if the pump current Ip**3** is a value A and the absolute value of the slope G is a value G**1**, the carbon dioxide concentration derived will be a value B. Also, even if the pump current Ip**3** is the same value A, when the absolute value of the slope G is G**2** or G**3**, which is larger than G**1** (G**1**<G**2**<G**3**), the larger the absolute value of the slope G, the smaller the value of the derived carbon dioxide concentration. Although only three straight lines are illustrated in FIG. **9**, the correspondence relationship stored in the storage section **98** may include relationships of many straight lines with slightly different absolute values of slope G. Alternatively, the CPU **97** may derive the carbon dioxide concentration by appropriately performing interpolation such as linear interpolation based on the correspondence relationship illustrated in FIG. **9**. Instead of the correspondence relationship illustrated in FIG. **9**, a first correspondence relationship, which is a correspondence relationship between the pump current Ip**3** and the carbon dioxide concentration when the water concentration is assumed to be a predetermined value (e.g., 0%), and a second correspondence relationship, which is a correspondence relationship between the slope G and the correction amount of the carbon dioxide concentration, may be stored in the storage section **98**, respectively. In this case, the CPU **97** may derive the corrected carbon dioxide concentration by correcting the carbon dioxide concentration derived based on the pump current Ip**3** and the first correspondence relationship with the correction amount derived based on the slope G and the second correspondence relationship (e.g., subtracting the correction amount from the carbon dioxide concentration). The second correspondence relationship may be a correspondence relationship between the slope G and a correction amount of the pump current Ip**3**. In this case, the CPU **97** may correct the pump current Ip**3** using the correction amount based on the slope G and the second correspondence relationship, and derive the carbon dioxide concentration based on the corrected pump current Ip**3** and the first correspondence relationship.

[0107] In the above embodiment, the CPU **97** detects the NOx concentration, the carbon dioxide concentration, the water concentration, and the oxygen concentration, but the CPU **97** is sufficient to detect at least the NOx concentration and the carbon dioxide concentration. For example, at least one of steps S**125** and S**140** in the control routine of FIG. **7** may be omitted. The order in which the CPU **97** detects the NOx concentration, the carbon dioxide concentration, the water concentration, and the oxygen concentration in the control routine of FIG. **7** may be interchanged, and the detection of two or more types of concentrations may be performed in parallel.

[0108] In the above-described embodiment, the CPU **97** corrects the NOx concentration using the water concentration, but may not correct the NOx concentration. Alternatively, the CPU **97** may determine whether the derived water concentration is within a predetermined tolerance which is regarded to have no effect on the accuracy of measurement of the NOx concentration, and when the derived water concentration is not within the predetermined tolerance, the CPU **97** may correct the NOx concentration.

[0109] In the above embodiment, in and after step S**110**, the adjustment pump control process, the first measurement pump control process, and the second measurement pump control process are continuously executed, but without being particularly limited thereto, at least one of these control processes may be suspended. For example, in step S**130**, the adjustment pump control process and the first measurement pump control process may be suspended, then the adjustment pump control process and the first measurement pump control process may be resumed with the target value V**1*** after the change.

[0110] In the above-described embodiment, the oxygen concentration adjustment chamber has the first internal cavity **20** and the second internal cavity **40**; however, the configuration is not limited thereto, and for example, the oxygen concentration adjustment chamber may further include another internal cavity, or one of the first internal cavity **20** and the second internal cavity **40** may

be omitted. Similarly, in the above-described embodiment, the adjustment pump cell has the main pump cell **21** and the auxiliary pump cell **50**; however, the configuration is not limited thereto, and for example, the adjustment pump cell may include another pump cell, or one of the main pump cell **21** and the auxiliary pump cell **50** may be omitted. For example, when the oxygen concentration in the measurement-object gas can be sufficiently reduced by the main pump cell **21** only, the auxiliary pump cell **50** may be omitted. FIG. **10** is a cross-sectional schematic view of sensor element **201**, which is one example of a sensor element that does not include the auxiliary pump cell **50**. In FIG. **10**, the same codes are used for the same components as those illustrated in FIG. **1**, and a detailed explanation is omitted. Sensor element **201** does not include the auxiliary pump cell **50**, and it also does not include the third diffusion control section **30** or the second internal cavity **40**. As a result, the first internal cavity **20** and the fourth diffusion control section **60** are adjacent to each other. In addition, the sensor element **201** does not include the auxiliary pump control oxygen partial pressure detection sensor cell **81**. When controlling the sensor element **201** that omits the auxiliary pump cell **50** in this way, the controller **96** only needs to perform the main pump control process as the adjustment pump control process. In the main pump control process, the above-described setting of the target value V**0*** based on the pump current Ip**1** may be omitted. Specifically, a predetermined target value V**0*** may be pre-stored in the storage section **98**, and the controller **96** may control the main pump cell **21** by performing feedback control on the voltage Vp**0** of the variable power supply **24** so that the voltage V**0** reaches the target value V**0***. When the auxiliary pump cell **50** is omitted, the voltage V**0** corresponds to the adjustment voltage (the voltage V**1** in the above embodiment), and the target value V**0*** corresponds to the adjustment voltage target value (the target value V**1*** in the above embodiment). Therefore, CPU **97** can detect the water concentration and the carbon dioxide concentration in the same way as the above embodiment, based on the change in the pump current Ip**2** which flows during execution of the adjustment pump control process and the first measurement pump control process when at least one of the target values V**0*** and V**2*** is changed. When the oxygen concentration adjustment chamber further includes another internal cavity in addition to the first internal cavity **20** and the second internal cavity **40**, and the adjustment pump cell has three or more pump cells, the target value of the voltage in the control process of the most downstream pump cell among the three or more pump cells, in other words, the pump cell disposed closest to the measurement chamber corresponds to the adjustment voltage target value. The current which flows by the control process of the most upstream pump cell among the three or more pump cells, in other words, the pump cell disposed closest to the gas inlet port **10** corresponds to the adjustment pump current.

[0111] In the above embodiment, the inner pump electrode **22** is a cermet electrode composed of Pt and ZrO.sub.2 and containing 1% of Au, but is not limited thereto. The inner pump electrode **22** may contain a noble metal with catalytic activity. As the noble metal with catalytic activity, for example, at least one of Pt, Rh, Ir, Ru or Pd may be mentioned. However, as in the above-described embodiment, the inner pump electrode **22** preferably contains Pt as the noble metal with catalytic activity. The inner pump electrode **22** preferably contains a noble metal with catalytic activity and Au. As in the inner pump electrode **22**, the auxiliary pump electrode **51** preferably contains a noble metal with catalytic activity, and further preferably contains Au. When the inner pump electrode **22** and the auxiliary pump electrode **51** contain Au, the catalytic activity for NOx and carbon dioxide is inhibited, thus reduction of NOx and carbon dioxide in the first internal cavity **20** and the second internal cavity **40** can be inhibited. The first measurement electrode **44** may contain a noble metal with catalytic activity. The first measurement electrode **44** preferably contains Rh and a noble metal with catalytic activity other than Rh (for example, at least one of Pt, Ir, Ru or Pd). The first measurement electrode **44** further preferably contains Rh and Pt. The first measurement electrode **44** containing Rh can promote the reduction of NOx in the third internal cavity **61**. The outer pump electrode **23**, the reference electrode **42** and the measurement electrode **44** each preferably contain the above-mentioned noble metal with catalytic activity. The electrodes **22**, **23**, **42**, **44**, **51**, **67** are

each preferably a cermet containing a noble metal and an oxide (e.g., ZrO.sub.2) having oxygen ion conductivity, and one or more of these electrodes may not be a cermet. The electrodes **22**, **23**, **42**, **44**, **51**, **67** are each preferably a porous body, but one or more of these electrodes may not be a porous body.

[0112] Although it was not explained in the above embodiment, the target values V**0*** and V**1*** are preferably values each between 300 mV and less than 400 mV. If the target values V**0*** and V**1*** are each 300 mV or more, the main pump cell **21** and auxiliary pump cell **50** can sufficiently pump out the oxygen in the oxygen concentration adjustment chamber. If the target values V**0*** and V**1*** are each less than 400 mV, the reduction of NOx and carbon dioxide in the oxygen concentration adjustment chamber can be suppressed. The target value V**2*** is preferably a value between 400 mV and 500 mV. If the target value V**2*** is 400 mV or more, then the NOx around the first measurement electrode **44** can be sufficiently reduced. If the target value V**2*** is 500 mV or less, then the reduction of carbon dioxide in the third internal cavity **61** can be suppressed. The target value V**3*** is preferably a value between 1000 mV and 1500 mV. If the target value V**3*** is 1000 mV or more, the carbon dioxide around the second measurement electrode **67** can be sufficiently reduced. If the target value V**3*** is 1500 mV or less, the voltage Vp**3** does not become too high, so the sensor element **101** is prevented from becoming black and becoming unusable. The blackening of the sensor element **101** occurs when oxygen ions in the solid electrolyte become depleted due to the application of a high voltage, and electronic conduction in the solid electrolyte occurs.

[0113] Although it was not explained in the above embodiment, when the heater **72** generates heat to at least one of the temperature ranges of 700° C. or more and 900° C. or less, the temperatures of the inner pump electrode **22**, the auxiliary pump electrode **51**, the first measurement electrode **44**, and the second measurement electrode **67** are respectively denoted as Tp, Tq, Tm**1**, and Tm**2**, it is preferable to configure the gas sensor **100** so that Tp>Tq>Tm**1** and Tp>Tq>Tm**2**. The main pump cell **21** pumps out the largest amount of oxygen from the measurement-object gas flow section, followed by the auxiliary pump cell **50**, and the first measurement pump cell **41** and the second measurement pump cell **66** pump out relatively small amounts, so by satisfying the above temperature relationship, the pumping capacity of the main pump cell **21** and the auxiliary pump cell **50** can be sufficiently high. Each of the temperatures Tp, Tq, Tm**1**, and Tm**2** is preferably 1000° C. or less to prevent cracking of the sensor element **101**. Temperature Tp is preferably 600° C. or higher because the main pump cell **21** can sufficiently pump out oxygen. Temperature Tp is preferably 900° C. or lower because it can suppress the reduction of NOx in the first internal cavity **20**. Temperature Tq is preferably 600° C. or higher because the auxiliary pump cell **50** can sufficiently pump out oxygen. Temperature Tq is preferably 900° C. or lower because it can inhibit the reduction of NOx in the second internal cavity **40**. Temperature Tm**1** is preferably 500° C. or higher because the first measurement pump cell **41** can sufficiently pump out the oxygen generated from NOx. Temperature Tm**2** is preferably 600° C. or higher, as the second measurement pump cell **66** is able to sufficiently pump out the oxygen produced from carbon dioxide. Adjustment of the temperature Tp, the temperature Tq, the temperature Tm**1**, and the temperature Tm**2** can be carried out by adjusting the shape and the arrangement of the heater **72**, for example.

[0114] In the above-described embodiment, the outer pump electrode **23** plays a role as the electrode (also referred to as an outer main pump electrode) to be paired with the inner pump electrode **22** in the main pump cell **21**, plays a role as the electrode (also referred to as an outer auxiliary pump electrode) to be paired with the auxiliary pump electrode **51** in the auxiliary pump cell **50**, plays a role as the electrode (also referred to as an first outer measurement electrode) to be paired with the first measurement electrode **44** in the first measurement pump cell **41**, and plays a role as the electrode (also referred to as an second outer measurement electrode) to be paired with the second measurement electrode **67** in the second measurement pump cell **66**; however, the configuration is not limited thereto. One or more of the outer main pump electrode, the outer auxiliary pump electrode, the first outer measurement electrode, and the second outer measurement

electrode may be provided separately from the outer pump electrode **23** outside the element body so as to be in contact with the measurement-object gas.

[0115] In the above-described embodiment, the element body of the sensor element **101** is a layered body having a plurality of solid electrolyte layers (layers **1** to **6**), but is not limited thereto. The element body of the sensor element **101** may include at least one oxygen-ion-conductive solid electrolyte layer. For example, in FIG. **1**, the layers **1** to **5** other than the second solid electrolyte layer **6** may be layers (e.g., layers composed of alumina) composed of a material other than that of solid electrolyte layers. In this case, the electrodes of the sensor element **101** may be disposed in the second solid electrolyte layer **6**. For example, the first measurement electrode **44** and the second measurement electrode **67** in FIG. **1** may be disposed on the lower surface of the second solid electrolyte layer **6**. Also, the reference gas inlet space **43** may be provided in the spacer layer **5** instead of the first solid electrolyte layer **4**, the reference gas inlet layer **48** may be provided between the second solid electrolyte layer **6** and the spacer layer **5** instead of between the first solid electrolyte layer **4** and the third substrate layer **3**, and the reference electrode **42** may be provided rearward of the third internal cavity **61** and on the lower surface of the second solid electrolyte layer **6**.

[0116] In the above-described embodiment, the controller **96** sets (feedback-controls) the target value V0* of the voltage V0 based on the pump current Ip1 so that the pump current Ip1 reaches the target value Ip1*, and feedback-controls the voltage Vp0 so that the voltage V0 reaches the target value V0*, but may perform another control. For example, the controller **96** may feedback-control the voltage Vp0 based on the pump current Ip1 so that the pump current Ip1 reaches the target value Ip1*. In other words, the controller **96** may omit acquisition of the voltage V0 from the main pump control oxygen partial pressure detection sensor cell **80** and setting of the target value V0*, and may directly control the voltage Vp0 (eventually, control the pump current Ip0) based on the pump current Ip1.

Claims

1. A gas sensor comprising: a sensor element including an element body including an oxygen-ion-conductive solid electrolyte layer and internally provided with a measurement-object gas flow portion that receives a measurement-object gas and causes the measurement-object gas to flow therethrough, a first measurement pump cell constituted by including an first inner measurement electrode disposed in a first measurement chamber of the measurement-object gas flow portion, the first measurement pump cell being configured to pump out oxygen in the first measurement chamber to an outside of the element body, a second measurement pump cell constituted by including an second inner measurement electrode disposed in a second measurement chamber located downstream of the first measurement chamber of the measurement-object gas flow portion, the second measurement pump cell being configured to pump out oxygen in the second measurement chamber to an outside of the element body, an adjustment pump cell constituted by including an inner adjustment electrode disposed in an oxygen concentration adjustment chamber located upstream of the first measurement chamber of the measurement-object gas flow portion, the adjustment pump cell being configured to adjust an oxygen concentration in the oxygen concentration adjustment chamber, and a reference electrode disposed inside the element body to come into contact with a reference gas; and a control apparatus that performs an adjustment pump control process of adjusting the oxygen concentration in the oxygen concentration adjustment chamber by controlling the adjustment pump cell so that an adjustment voltage that is a voltage across the reference electrode and the inner adjustment electrode reaches an adjustment voltage target value, a first measurement pump control process of pumping out oxygen in the first measurement chamber by controlling the first measurement pump cell so that a first measurement voltage that is a voltage across the reference electrode and the first inner measurement electrode

reaches a first measurement voltage target value, and a second measurement pump control process of pumping out oxygen in the second measurement chamber by controlling the second measurement pump cell so that a second measurement voltage that is a voltage across the reference electrode and the second inner measurement electrode reaches a second measurement voltage target value, wherein the control apparatus detects a NOx concentration in the measurement-object gas based on a first measurement pump current which flows when the oxygen produced due to reduction of NOx in the first measurement chamber is pumped out by the first measurement pump control process, and the control apparatus detects a carbon dioxide concentration in the measurement-object gas based on a second measurement pump current which flows when the oxygen produced due to reduction of carbon dioxide in the second measurement chamber is pumped out by the second measurement pump control process, and a change in the first measurement pump current which flows during execution of the adjustment pump control process and the first measurement pump control process when at least one of the adjustment voltage target value or the first measurement voltage target value is changed.

2. The gas sensor according to claim 1, wherein the control apparatus detects a water concentration in the measurement-object gas based on the change in the first measurement pump current.

3. The gas sensor according to claim 2, wherein the control apparatus derives a total value of a carbon dioxide concentration and a water concentration in the measurement-object gas based on the second measurement pump current, and detects the carbon dioxide concentration in the measurement-object gas by subtracting the water concentration detected from the total value.

4. The gas sensor according to claim 1, wherein the control apparatus detects the oxygen concentration in the measurement-object gas based on an adjustment pump current which is caused to flow by the adjustment pump control process.

5. The gas sensor according to claim 1, wherein the oxygen concentration adjustment chamber has a first internal cavity, and a second internal cavity provided downstream of the first internal cavity and upstream of the measurement chamber, the adjustment pump cell has a main pump cell that adjusts an oxygen concentration in the first internal cavity, and an auxiliary pump cell that adjusts an oxygen concentration in the second internal cavity, the inner adjustment electrode has an inner main pump electrode that is disposed in the first internal cavity and constitutes part of the main pump cell, and an inner auxiliary pump electrode that is disposed in the second internal cavity and constitutes part of the auxiliary pump cell, and the adjustment pump control process includes a main pump control process of controlling the main pump cell to adjust the oxygen concentration in the first internal cavity, and an auxiliary pump control process of controlling the auxiliary pump cell so that the adjustment voltage reaches the adjustment voltage target value.

6. The gas sensor according to claim 1, wherein the inner adjustment electrode contains a noble metal with catalytic activity and Au.

7. The gas sensor according to claim 1, wherein the first inner measurement electrode contains Rh and a noble metal with catalytic activity other than Rh.