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(11)(21) **2 746 336**

(12) **BREVET CANADIEN**
CANADIAN PATENT

(13) **C**

(86) **Date de dépôt PCT/PCT Filing Date:** 2008/12/19
(87) **Date publication PCT/PCT Publication Date:** 2010/06/24
(45) **Date de délivrance/Issue Date:** 2014/05/27
(85) **Entrée phase nationale/National Entry:** 2011/06/09
(86) **N° demande PCT/PCT Application No.:** CA 2008/002232
(87) **N° publication PCT/PCT Publication No.:** 2010/069036

(51) **Cl.Int./Int.Cl.** *G01L 9/02* (2006.01),
G01L 21/12 (2006.01)

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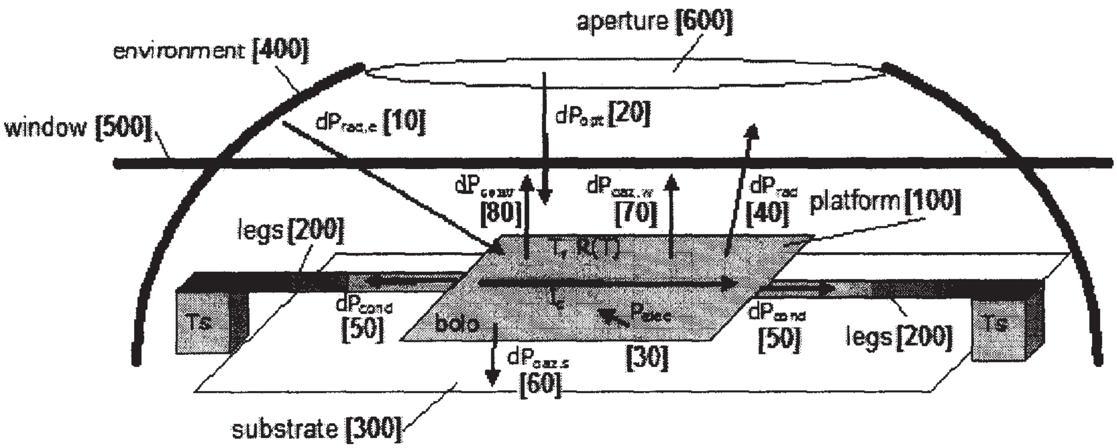
(54) **Titre :** CAPTEUR DE PRESSION DE GAZ A MICRO-THERMISTANCE
(54) **Title:** MICRO-THERMISTOR GAS PRESSURE SENSOR



(57) **Abrégé/Abstract:**

The invention provides an apparatus and method for precisely measuring gas pressure over a large dynamic range and with good immunity to temperature fluctuations, encompassing applications such as gas sensing, bolometer imaging and industrial process monitoring. The micro-thermistor gas pressure sensor assembly consists of a suspended platform micro-thermistor sensor device exposed to the gas pressure of a given atmospheric environment, an electrical readout circuit connected to the suspended platform micro-thermistor sensor device, wherein the suspended platform micro-thermistor sensor device acts as a variable electrical resistance in said readout electrical circuit, a binary-wave voltage source connected to the suspended platform micro-thermistor sensor device, and an ohmmeter.

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
24 June 2010 (24.06.2010)

PCT

(10) International Publication Number
WO 2010/069036 A1

(51) International Patent Classification:
G01L 9/02 (2006.01) ***G01L 21/12*** (2006.01)

(21) International Application Number:
PCT/CA2008/002232

(22) International Filing Date:
19 December 2008 (19.12.2008)

(25) Filing Language: English

(26) Publication Language: English

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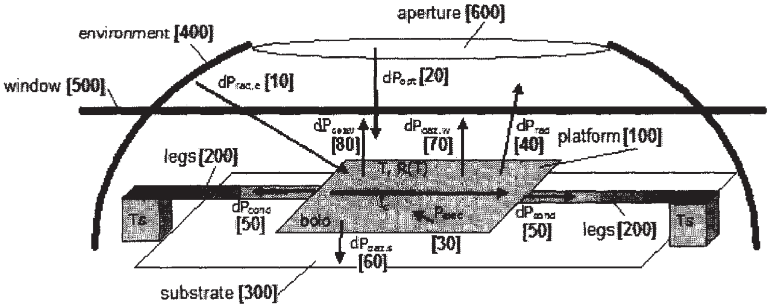
(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, NO, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report (Art. 21(3))*

(54) Title: MICRO-THERMISTOR GAS PRESSURE SENSOR

FIG. 1



(57) Abstract: The invention provides an apparatus and method for precisely measuring gas pressure over a large dynamic range and with good immunity to temperature fluctuations, encompassing applications such as gas sensing, bolometer imaging and industrial process monitoring. The micro-thermistor gas pressure sensor assembly consists of a suspended platform micro-thermistor sensor device exposed to the gas pressure of a given atmospheric environment, an electrical readout circuit connected to the suspended platform micro-thermistor sensor device, wherein the suspended platform micro-thermistor sensor device acts as a variable electrical resistance in said readout electrical circuit, a binary-wave voltage source connected to the suspended platform micro-thermistor sensor device, and an ohmmeter.

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WHAT IS CLAIMED IS:

1. A gas pressure sensor assembly comprising:

at least one suspended platform micro-thermistor sensor device exposed to the gas pressure of a given atmospheric environment, said at least one sensor device being at least partially encased in a gas pressure environment, said sensor device having a thermal conductivity that changes in response to a change in said gas pressure;

an electrical readout circuit connected to each of said at least one suspended platform micro-thermistor sensor device, wherein each of said at least one suspended platform micro-thermistor sensor device acts as a variable electrical resistor in said electrical readout circuit;

a binary-wave voltage source connected to each of said at least one suspended platform micro-thermistor sensor device, said source generating a binary-wave voltage signal having a frequency lower than 100 Hertz; and

an ohmmeter.

2. A gas pressure sensor assembly of claim 1, wherein said at least one suspended platform micro-thermistor sensor device has a physical dimension between 0.1 μm and 250 μm.

3. A gas pressure sensor assembly of claim 1, wherein said at least one suspended platform micro-thermistor sensor device is made of a material having a Temperature Coefficient of Resistance (TCR) of at least 0.5% per degree Kelvin.

4. A gas pressure sensor assembly of claim 1, wherein said at least one suspended platform micro-thermistor sensor device is made of vanadium oxide.

5. A gas pressure sensor assembly of claim 1, wherein said at least one suspended platform micro-thermistor sensor device is made of amorphous silicon.

6. A gas pressure sensor assembly of claim 1, wherein said gas is air.

7. A gas pressure sensor assembly of claim 1, wherein said gas is nitrogen.

8. A gas pressure sensor assembly of claim 1, wherein said gas is oxygen.

9. A gas pressure sensor assembly of claim 1, wherein said gas is a noble gas.

10. A gas pressure sensor assembly of claim 1, wherein said gas is a mixture of several gases.

11. A gas pressure sensor assembly of claim 1, wherein said gas pressure is between 10^{-4} to 10^4 Torr.

12. A gas pressure sensor assembly of claim 1, wherein said gas pressure is below 10^{-4} Torr.

13. A gas pressure sensor assembly of claim 1, wherein said gas pressure is above 10^4 Torr.

14. A gas pressure sensor assembly of claim 1, wherein said atmospheric environment has a physical volume of at least 1 picoliter.

15. A gas pressure sensor assembly of claim 1, wherein said readout electrical circuit is a CMOS device.

16. A gas pressure sensor assembly of claim 1, wherein said readout electrical circuit comprises at least one load resistor.

17. A gas pressure sensor assembly of claim 1, wherein said readout electrical circuit comprises electrical resistors, capacitors and inductors.

18. A gas pressure sensor assembly of claim 1, wherein said electrical readout circuit is connected to a plurality of said at least one suspended platform micro-thermistor sensor device.

19. A gas pressure sensor assembly of claim 1, wherein said ohmmeter is a resistive-capacitive (RC), or resistive-inductive (RL), or resistive-inductive-capacitive (RLC) electronic circuit.

20. A method for gas pressure measurement comprising the steps of:

electrically exciting a suspended platform micro-thermistor sensor device with a binary-wave voltage signal having a frequency lower than 100 Hertz to allow reaching a steady-state thermal regime during each half-cycle of said voltage signal;

measuring the ohmic responsivity of said suspended platform micro-thermistor sensor device using an ohmmeter, wherein said ohmmeter has an electrical response proportional to said ohmic responsivity; and

determining gas pressure from said ohmic responsivity, said gas pressure being related to said ohmic responsivity through a polynomial expression involving at least five parameters, said parameters being selected from the group consisting of: temperature; distance to substrate; surface area; distance to environment; emissivity of said micro-thermistor sensor device; gas composition; substrate temperature; environment temperature; and thermal conductivity of legs supporting said suspended platform.

21. The method for gas pressure measurement of claim 20, wherein said measuring of the ohmic responsivity applies to a plurality of suspended platform micro-thermistor sensor devices having the same physical characteristics.

22. The method for gas pressure measurement of claim 20, wherein said binary-wave voltage signal induces an incremental change of temperature of said suspended platform micro-thermistor, from temperature A to temperature B.

23. The method for gas pressure measurement of claim 22, wherein said incremental change of temperature of said suspended platform micro-thermistor is kept constant.

24. The method for gas pressure measurement of claim 22, wherein said temperature A and temperature B of said suspended platform micro-thermistor are kept constant.

MICRO-THERMISTOR GAS PRESSURE SENSOR

FIELD OF THE INVENTION

The present invention relates to a micro-thermistor gas pressure sensor.

BACKGROUND OF THE INVENTION

A conventional gas pressure sensor, such as a Pirani gauge, is calibrated against several known pressures to determine a relationship between ambient pressure and power dissipated by the sensor. On one hand, since a Pirani gauge may be designed to have a wide dynamic range and be relatively simple and inexpensive, there is a need to be able to use this type of pressure gauge as a substitute for much higher priced gauges such as capacitance manometers and ionization gauges. On a second hand, the growing markets of high-performance wafer-level micro-packaging require miniaturization of the gas pressure sensors and integration to standard CMOS processes and MEMS micro-devices such as bolometers, gyroscopes and accelerometers.

US 2007/0069133 A1 relates to a gas pressure sensor combining Pirani-like functionality and MEMS integration. Pressure sensors based on MEMS micro-sensor devices can achieve both low-cost and CMOS-compatible integration. However, existing MEMS micro-sensor devices may show inaccurate pressure readings when subjected to temperature fluctuations, especially at low pressures. US 2007/0069133 A1 exhibits such temperature sensitivity, because the electrical response of the sensor depends on the substrate and environment temperatures by virtue of the temperature dependency of the variable resistance. Furthermore, the method for pressure measurement relies on an absolute voltage reading instead of differential voltage readings, wherein absolute voltage reading may be subjected to inaccuracies if fabrication errors occur from one sensor to the other.

Gas pressure micro-sensors showing relative immunity to temperature fluctuations have been developed. US 6,945,119 B2 and US 7,331,237 B2 relate to temperature-compensated micro-sensors integrated in a CMOS circuit. Temperature fluctuation compensation is achieved using a combination of temperature-sensitive and temperature-insensitive elements coupled to a bridge readout circuit. However, temperature compensation of these gas pressure sensors is achieved at the cost of structural complexity of the device and readout circuit, which impede integration of such sensors into MEMS micro-devices. Furthermore, the method for pressure measurement relies on an absolute voltage reading instead of differential voltage readings which lead to inaccuracies if fabrication errors occur from one gauge to the other.

It is the object of the present invention to provide an apparatus and method allowing 1) miniaturization of the wide-dynamic-range pressure sensors to address the high-performance micro-packaging markets and 2) integration to standard CMOS processes and MEMS micro-devices such as bolometers, gyroscopes and accelerometers, and 3) relative immunity of the pressure sensors to temperature fluctuations and fabrication errors by the use of differential voltage readings.

SUMMARY OF THE INVENTION

The invention presents an apparatus and method for precisely measuring gas pressure in atmospheric environments as small as 1 picoliter. The micro-thermistor gas pressure sensor and method of operation described herein provides gas pressure measurements over a large dynamic range and with good immunity to temperature fluctuations. The micro-thermistor gas pressure sensor is compatible with standard CMOS fabrication processes and readout circuits.

The gas pressure sensing element of the present invention includes a suspended platform micro-thermistor device, which is a suspended electrical transducer that changes electrical resistance with a change of temperature. The gas pressure sensor assembly comprises the suspended platform micro-thermistor device and a readout electrical circuit driving the micro-thermistor device. When the micro-thermistor is electrically excited and heated, its temperature at equilibrium is a function of applied electrical power and of thermal transfer to the environment. The gas is part of this environment and the heat transferred from the micro-thermistor device to the environment is a function of the gas pressure. The principle of gas pressure measurement consists in heating the micro-thermistor device with a binary-wave electrical excitation, measuring its thermal conduction to the environment, and determining the gas pressure from the measured thermal conduction. Specifically, the method consists in measuring the ohmic responsivity of the suspended platform micro-thermistor with a binary-wave electrical excitation. The ohmic responsivity is a direct measurement of the thermal conductivity of the suspended platform micro-thermistor sensor device, the latter being related to gas pressure.

Thus, in accordance with an aspect of the invention, there is provided A gas pressure sensor assembly comprising:

at least one suspended platform micro-thermistor sensor device exposed to the gas pressure of a given atmospheric environment, said at least one sensor device being at least partially encased in a gas pressure environment, said sensor device having a thermal conductivity that changes in response to a change in said gas pressure;

an electrical readout circuit connected to each of said at least one suspended platform micro-thermistor sensor device, wherein each of said at least one suspended platform micro-thermistor sensor device acts as a variable electrical resistor in said electrical readout circuit;

a binary-wave voltage source connected to each of said at least one suspended platform micro-thermistor sensor device, said source generating a binary-wave voltage signal having a frequency lower than 100 Hertz; and

an ohmmeter.

In accordance with another aspect of the invention, there is provided a method for gas pressure measurement comprising the steps of:

electrically exciting a suspended platform micro-thermistor sensor device with a binary-wave voltage signal having a frequency lower than 100 Hertz to allow reaching a steady-state thermal regime during each half-cycle of said voltage signal;

measuring the ohmic responsivity of said suspended platform micro-thermistor sensor device using an ohmmeter, wherein said ohmmeter has an electrical response proportional to said ohmic responsivity; and

determining gas pressure from said ohmic responsivity, said gas pressure being related to said ohmic responsivity through a polynomial expression involving at least five parameters, said parameters being selected from the group consisting of: temperature; distance to substrate; surface area; distance to environment; emissivity of said micro-thermistor sensor device; gas composition; substrate temperature; environment temperature; and thermal conductivity of legs supporting said suspended platform.

These and other features and advantages of the invention will be apparent to those skilled in the art from the following detailed description of preferred embodiments, taken together with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG 1. is a schematic representation of the micro-thermistor gas pressure sensing element and its surroundings, including the heat budget of the system.

FIG. 2. is a chart showing ohmic responsivity Ω as function of air pressure p, for a 70x70 μm^2 micro-thermistor gas pressure sensor.

FIG. 3. shows an exemplary embodiment of the gas pressure sensor assembly.

FIG. 4. shows another exemplary embodiment of the gas pressure sensor assembly.

FIG. 5. shows a graph of the effect of temperature fluctuations of (T_b,T_s,T_{env}) on the micro-thermistor gas pressure sensor and deviations from an ideal 5-parameter calibration equation determined by MonteCarlo simulation. The plot shows the statistical error (1σ) on pressure measurement under a temperature fluctuation of 1K (1σ) for T_b and 10K (1σ) for (T_s,T_{env}), for a 70x70 um^2 micro-thermistor gas pressure sensor.

DETAILED DESCRIPTION OF THE INVENTION

This invention presents an apparatus and method for measuring gas pressure in atmospheric environments as small as 1 picoliter, with pressure measurements performed over a large dynamic range and with good immunity to temperature fluctuations. The apparatus and method of the present invention are compatible with digital and analog readout circuits and CMOS fabrication processes.

Figure 1 is a schematic representation of the apparatus. The gas pressure sensing element consists of a micro-thermistor device comprising a suspended platform [100] and suspending legs [200] connecting the suspended platform to a substrate [300]. The micro-thermistor suspended platform [100] may have a width between 0.1µm and 250µm, a length between 0.1µm and 250µm, and a thickness between 0.1µm and 5µm. The suspending legs [200] must provide enough mechanical rigidity for suspending the micro-thermistor platform [100] at least 0.1µm above the substrate [300] and must provide a path for electrical connection from the suspended platform [100] to the substrate [300]. Standard CMOS fabrication processes can be used to fabricate the suspended platform micro-thermistor device on the substrate. The suspending legs [200] may be made of silicon nitride or silicon dioxide materials or any other materials procuring mechanical rigidity, coated with a metallic layer to procure electrical conductivity, and have a length between 1μm and 1000μm. The suspending legs [200] usually have smaller widths than the suspended platform [100] in order to procure thermal isolation between the suspended platform and the substrate [300]. The substrate [300] may consist of a silicon wafer or a CMOS electrical readout circuit or any CMOS integrated device. The substrate is partly or fully enclosed within a gas pressure environment [400] which may include a window [500] (e.g. infrared window or diaphragm or mask) for shielding the suspended platform [100] from excess infrared radiation coming from the environment [400], and may include an optical aperture [600] for providing the suspended platform [100] infrared radiation from a scene. The environment [400] must be large enough to entirely encapsulate the micro-thermistor suspended platform [100] and suspending legs [200]. Since the micro-thermistor suspended platform [100] and suspending legs [200] have micrometer-scale dimensions, the environment [400] encompassing the micro-thermistor device may have a volume as small as 1 picoliter (10^{-15} m^3). The environment [400] is filled with a gas that exerts pressure equally everywhere in the environment, including the top and bottom surfaces of the suspended platform [100]. The gas may be composed of air, oxygen, nitrogen, noble gas or any other gases including a mixture of several different gases.

The temperature of the micro-thermistor suspended platform [100] is a function of applied heating power and thermal transfers to the substrate and to the environment. Figure 1 shows the total heat budget of the system defined as the thermal transfers between the suspended platform [100] of the micro-thermistor and the substrate [300] and environment [400]. Specifically, the micro-thermistor suspended platform [100] receives heat from a plurality of sources:

- $P_{rad,e}$, by absorbing infrared radiation emitted by the environment [10].

- P_{opt}, by absorbing infrared radiation coming from the scene through the window [20]
- P_{elec}, by Joule heating when an electrical current is applied from the legs through the micro-thermistor suspended platform [30].

And the micro-thermistor suspended platform [100] dissipates heat to a plurality of thermal conduction paths:

- P_{rad}, by thermal radiation [40]
- P_{cond}, by thermal conduction to the substrate through the legs [50]
- $P_{gaz,s}$, by thermal conduction to the substrate through the gas [60]
- $P_{gaz,w}$, by thermal conduction to the window through the gas [70]
- P_{conv}, by thermal convection to the window through the gas [80]

The dynamic analysis of the system is based on the use of heat transfer equation for the suspended platform [100] of the micro-thermistor. Taking into consideration the thermodynamic interactions between the micro-thermistor and its surroundings, it is well known in the art of thermal conduction that the following heat equation can be derived:

$$C\frac{d(\Delta T)}{dt}+G(\Delta T)=P$$

Where C is the thermal capacity of the suspended platform [100] of the micro-thermistor (in units of J/K), G its thermal conduction (in units of W/K) related to all the thermal dissipation mechanisms of the system [40] [50] [60] [70] [80], ΔT the incremental temperature change of the suspended platform [100] of the micro-thermistor with respect to the substrate [300] ($\Delta T = T_b - T_s$) (in units of K) and P is the power [10] incident [20] on the micro-thermistor or applied [30] to the micro-thermistor expressed in Watts. The main component of the power P, the applied electrical excitation P_{elec} [30], is related to the electrical resistance of the suspended platform [100] of the micro-thermistor R_b, the electrical potential V_b across the legs [200] of the micro-thermistor, and the electrical current i_b passing through the suspended platform [100] of the micro-thermistor.

The micro-thermistor suspended platform [100] may comprise a combination of silicon dioxide and silicon nitride thin films for procuring mechanical rigidity to the platform; a metallic thin film for procuring electrical conductivity to the platform; and a thermally sensitive thin film material for procuring change of electrical properties with a change of temperature of the platform. The thermally sensitive thin film material may consist of vanadium oxide, titanium oxide or amorphous silicon.

Vanadium oxide (such as VO_x with $1<x<3$) has received most attention as a micro-thermistor thermally sensitive thin film material because of the large temperature coefficient of resistance (TCR) of about 2% per Kelvin near 20°C. The properties of vanadium oxide films are dependent of the microstructure and crystallinity. These can be controlled by the experimental process parameters, such as the molecular precursors, heat treatments and controlled atmosphere. Other thermally sensitive thin film materials can be used for the micro-thermistor suspended platform [100] in order to procure change of electrical properties of the micro-thermistor with a change of temperature of the platform, ideally with a temperature coefficient of resistance (TCR) of at least 0.5% per Kelvin. The thermally sensitive thin film material is not limited to a specific material composition; it may consist of vanadium oxide, titanium oxide, amorphous silicon or any material or alloy with a temperature coefficient of resistance (TCR) of at least 0.5% per Kelvin.

The coefficient of thermal conduction G between the suspended platform [100] of the micro-thermistor and its surroundings [300] [400] can be described by the contribution of all the thermal dissipation mechanisms of the system [40] [50] [60] [70] [80]:

$$G = G_{leg} + G_{rad} + G_{gas} + G_{conv}$$

where G_{leg} is the coefficient of thermal conduction between the micro-thermistor suspended platform [100] and the substrate [300] through the micro-thermistor legs which determines the heat dissipation through the legs [50];

G_{rad} is the coefficient of thermal conduction between the micro-thermistor suspended platform [100] and the environment [400] by emitted infrared radiation which determines the heat dissipation through radiation [40];

G_{gas} is the coefficient of thermal conduction between the micro-thermistor suspended platform [100] and its surroundings through the gas, which comprises heat dissipation to the substrate [300] through the gas [60] and heat dissipation to the environment [400] through the gas [70]; and G_{conv} is the coefficient of thermal conduction between the micro-thermistor suspended platform [100] and its surroundings by gas convection [80].

LEG CONDUCTION:

The coefficient of thermal conduction G_{leg} between the micro-thermistor suspended platform [100] and the substrate [300] through the legs [200] depends on the leg length, leg cross-section and leg material. In practice, the coefficient of thermal conduction G_{leg} is not always known precisely and may depend on temperature, and the gas pressure measurement method herein described in this invention cancels the need for precise knowledge of this term of the equation. Typically, the coefficient of thermal conduction to the substrate through the legs is 10^{-6} W/K or less.

RADIATION:

The coefficient of thermal conduction Grad by emitted infrared radiation from the micro-thermistor suspended platform [100] and its surroundings [300] [400] depends on the surface area of the suspended platform [100] and on its spectral emissivity which could be a blackbody or non-blackbody function of temperature. For an ideal blackbody material, this coefficient of thermal conduction can be approximated as the sum of radiated power from the micro-thermistor bottom surface facing the substrate [300] and from the micro-thermistor top surface facing the environment [400]:

$$G_{rad} = \sigma\varepsilon\beta A\,(T_b^4 - T_s^4)/(T_b - T_s) + \sigma\varepsilon\beta A\,(T_b^4 - T_{env}^4)/(T_b - T_s) \simeq 4\sigma\varepsilon\beta A\,(T_s^3 + T_{env}^3)$$

where σ is the Stefan–Boltzmann constant, ε is the effective emissivity of the micro-thermistor suspended platform [100], A is its surface area, β is a form factor that includes thermal dissipation through other parts of the micro-thermistor structure, T_b is the micro-thermistor temperature, T_s is the substrate temperature and T_{env} is an effective environment temperature related to the hemispheric distribution of all thermal components of the environment seen by the micro-thermistor platform [100]. The right-hand side of the equation assumes that the temperature difference between the micro-thermistor and the substrate is small with respect to the absolute temperature of the micro-thermistor ($|T_b - T_s| << T_b$) which is valid to 1% error when the micro-thermistor is heated only by a few degrees Kelvin. In practice, the spectral emissivity ε of the platform and the temperatures (T_b, T_s, T_{env}) are not always known precisely, and consequently the coefficient of thermal conduction Grad is not always known precisely. The gas pressure measurement method herein described in this invention cancels the need for precise knowledge of these terms of the equation.

GAS CONDUCTION:

The coefficient of thermal conduction Ggas between the micro-thermistor suspended platform [100] and its surroundings through the gas, which comprises heat dissipation to the substrate [300] through the gas [60] and heat dissipation to the environment [400] through the gas [70], can be obtained by the kinetic theory of gases for the heat conduction in a gas between two parallel plates;

$$G_{\text{gas}} = \frac{\beta \cdot A}{\frac{ds}{\lambda_{\text{gas}_s}} + \frac{1}{\gamma_{\text{gas}} \cdot P}} + \frac{k \cdot \beta \cdot A}{\frac{de}{\lambda_{\text{gas}_e}} + \frac{1}{\gamma_{\text{gas}} \cdot P}}$$

Where p is the gas pressure, d_s the distance between the micro-thermistor suspended platform [100] and the substrate [300], d_e the distance between the micro-thermistor suspended platform [100] and the window [500], A is the surface area of the micro-thermistor suspended platform [100], β is a form factor that includes thermal dissipation through other parts of the micro-thermistor structure, and $k = (T_b - T_{env})/(T_b - T_s)$. In the absence of window [500], d_e can be defined as an effective distance between the micro-thermistor suspended platform [100] and the environment [400]. λ_{gas} is the thermal conductivity of the gas in the high-pressure regime and γ_{gas} is the thermal conductivity per unit pressure and length in the low-pressure regime. The gas conductivity λ_{gas} depends on the gas temperature:

$$\lambda_{gas} = \lambda_o + (d\lambda/dT_s).(T_g - T_o)$$

Where T_g is an effective gas temperature given by $T_g = (1-\eta)T_x + \eta T_b$, where $T_x = T_s$ (substrate side) or $T_x = T_{env}$ (environment side) and η is a thermal distribution factor; typically η ~ 0.5. For air: $d\lambda/dT = 7.2167e\text{-}005$ W/mK^2 and $\lambda_o = 0.0243$ W/mK at $T_o =$

273K. Other gases may show different coefficients. In practice, the gas conductivities (Λ_{gas}, γ_{gas}, η), the temperatures (T_b, T_s, T_{env}), and the dimensional terms (d_s, d_e, β are not always known precisely, and the gas pressure measurement method herein described in this invention cancels the need for precise knowledge of these terms of the equation.

CONVECTION:

The heat transferred by free convection [80] from the micro-thermistor suspended platform [100] into the gas to the environment [400] at the temperature T_{env} is given by

$$P_{conv} = G_{conv} \cdot \Delta T = A\ h\ (T_b - T_{env})$$

Where h is the convection coefficient of the gas [in air h = 5 W/m^{2}K]. In practice, the convection coefficient h is not always known precisely, and the gas pressure measurement method herein described in this invention cancels the need for precise knowledge of this term of the equation. For most cases encompassed within this invention, the thermal conduction G_{conv} by free air convection through gas movement is negligible compared to the thermal conduction G_{gas} through the gas.

The thermal conduction G between the suspended platform [100] of the micro-thermistor and its surroundings [300] [400] can also be described by the contribution from additional factors herein not mentioned, dependent on the micro-thermistor three-dimensional design and fabrication. In practice, these additional factors are not always known precisely, and the gas pressure measurement method herein described in this invention cancels the need for precise knowledge of these terms of the equation.

This invention thus relates to a microscopic thermistor apparatus for measuring gas pressure in atmospheric environments with volumes as small as 1 picoliter. The gas pressure sensing element consists of a suspended platform micro-thermistor device which is a transducer that changes electrical resistance with a change of temperature. The gas pressure sensor assembly comprises the suspended platform micro-thermistor device [100] and a readout circuit connected to the suspended platform for driving the micro-thermistor device electrically. When the micro-thermistor is electrically excited and heated, its temperature at equilibrium is a function of incident radiative power [10] [20] and applied electrical power [30], and of thermal transfer to the environment including all the heat dissipation mechanisms described above [40] [50] [60] [70] and [80]. Since the gas is part of this environment, and since the heat transferred from the micro-thermistor suspended platform [100] to the environment [400] and substrate [300] depends on gas pressure [60] [70], the micro-thermistor apparatus can be used as a microscopic gas pressure sensing device.

Gas pressure measurement method:

The suspended platform of the micro-thermistor [100] is electrically excited by voltage source connected to it. Since the micro-thermistor device is electrically resistive, it is well known in the art that this electrical excitation procures heating to the micro-thermistor by virtue of the Joule effect. The temperature of the micro-thermistor at equilibrium is a function of applied electrical power [30] and of thermal transfer to the substrate [300] and to the environment [400] via the plurality of thermal dissipation mechanisms previously described [10] [20] [40] [50] [60] [70] and [80]. The gas is part of the environment [400] and the heat transferred from the micro-thermistor device to the environment [60] [70] is a function of the gas pressure exerted within the environment. The principle of gas pressure measurement thus consists of heating the suspended platform micro-thermistor device [100] by Joule heating [30] and of measuring the thermal conductivity of the micro-thermistor device to its surroundings, and determining the gas pressure from the measured thermal conduction.

The micro-thermistor gas sensor of the present invention is highly sensitive to the radiative thermal conduction G_{rad} and to the leg thermal conduction G_{leg}. The influence of radiation conduction and leg conduction on the micro-thermistor suspended platform [100] must be considered in the proposed method of gas pressure measurement in order to prevent large errors of measurements to occur, since the power absorbed [10] [20] and dissipated [40] [50] by radiation and by leg conduction is of the same order of magnitude as the power dissipated through the gas [60] [70] [80]. To improve sensor tolerance against radiation conduction and leg conduction it is proposed to perform a double measurement at two fixed micro-thermistor temperatures. This double-measurement method herein described in this invention cancels the need for precise knowledge of the radiation term G_{rad}, of the conduction through the legs G_{leg}, of convection through the gas G_{conv} and of any additional thermal conduction factors herein not mentioned, since these factors are not always known precisely in practice.

Specifically, the method of measuring gas pressure with the suspended platform micro-thermistor assembly of the present invention is based on probing the thermal response of the micro-thermistor device with a binary-wave electrical excitation [30]. The binary-wave electrical excitation may consist of a step-function voltage signal with a minimum voltage (V_1) followed by a maximum voltage (V_2), the difference between the minimum and maximum voltages corresponds to the amplitude of the binary-wave signal, $\Delta V = V_2 - V_1$. The voltage V_b applied to the micro-thermistor depends on the electrical excitation V and on the transfer function f of the readout circuit, $V_b = f V$. The binary-wave signal generates an incremental amount of electrical heating power [30] applied to the micro-thermistor suspended platform [100], $dP_b =$

V_{b2}^2/R_{b2} - V_{b1}^2/R_{b1}, leading to an incremental change of micro-thermistor electrical resistance, $dR_b = R_{b2} - R_{b1}$, where R_{b1} and R_{b2} are the electrical resistances of the micro-thermistor suspended platform at temperatures T_{b1} and T_{b2} respectively. Experimentally, the resistance of the micro-thermistor R_b is used instead of the temperature T_b; the temperature cannot be measured experimentally but the temperature is completely determined by the electrical resistance of the micro-thermistor by virtue of its temperature coefficient of resistance (TCR). Generally, both T_{b1} and T_{b2} are a few degrees above substrate/environment temperatures T_s and T_{env}, and the difference between T_{b1} and T_{b2} is a few degrees Kelvin.

Alternatively, the binary-wave electrical excitation may consist of a periodic square-wave voltage signal with minimum voltages (V_1) followed periodically by maximum voltages (V_2) with a frequency ω, the difference between the minimum and maximum voltages corresponds to the amplitude of the periodic binary-wave signal, $\Delta V = V_2 - V_1$, and to an incremental amount of electrical heating power per period of the binary-wave, $dP_b = V_{b2}^2/R_{b2} - V_{b1}^2/R_{b1}$, and to an incremental change of micro-thermistor electrical resistance, $dR_b = R_{b2} - R_{b1}$. The gas pressure measurement method consists of measuring the ohmic responsivity dR_b/dP_b of the micro-thermistor device in response to the binary-wave electrical excitation; the ohmic responsivity is a direct measurement of the thermal conductivity of the suspended platform micro-thermistor device, the later being related to gas pressure as described previously.

Taking into account the thermodynamic interactions between the micro-thermistor and its surroundings, comprising all the thermal dissipation mechanisms [40] [50] [60] [70] [80] previously described, the following heat equation can be derived:

$$C\frac{d(\Delta T)}{dt} + G(\Delta T) = P$$

Where C is the thermal capacity of the micro-thermistor platform [100], G its coefficient of thermal conduction comprising every heat dissipation mechanisms previously defined, and ΔT the temperature change of the micro-thermistor suspended platform [100] with respect to the substrate [300]: $\Delta T = T_b - T_s$. The right hand side of the equation represents the power applied to the micro-thermistor suspended platform which may consist principally of the binary-wave electrical excitation supplying an incremental amount of electrical heating power to the micro-thermistor [30], $P = P_b$. As seen previously, the coefficient of thermal conduction G depends on several factors, including the micro-thermistor temperature T_b, and may take the form $G = G(T_b)$. Steady-state is achieved after a time period of $t > C/G$, typically 100 msec or more, from which d/dt tends to zero. At steady-state, and to first order, the solution for the thermal conductivity takes the form,

$$G + \frac{dG}{dT_b}(T_b - T_s) = \frac{P_b}{(T_b - T_s)}$$

Where P_b is defined as the electrical heating power needed to bring the micro-thermistor platform from the temperature T_s to the temperature T_b. The same relation applies to the difference of electrical heating power between two measurements made at temperatures T_{b1} and T_{b2},

$$G + \frac{dG}{dT_b}(T_b - T_s) = \frac{(P_{b2} - P_{b1})}{(T_{b2} - T_{b1})} = \frac{dP_b}{dT_b}$$

Since the micro-thermistor electrical resistance is function of temperature, by virtue of its non-zero Temperature Coefficient of Resistance, $\alpha = (dR_b/dT_b)/R_b$, the solution on thermal conductivity can be expressed by:

$$G_{leg} + G_{radiation} + G_{gas} + G_{conv} + \frac{dG}{dT_b}(T_b - T_s) = \alpha R_b \frac{dP_b}{dR_b} = \frac{\alpha R_b}{\Omega}$$

Where α is the temperature coefficient of resistance (TCR) of the micro-thermistor and R_b its electrical resistance at the reference temperature T_s. The term $\Omega = dR_b/dP_b$ is the ohmic responsivity of the micro-thermistor suspended platform. The ohmic responsivity Ω of the micro-thermistor suspended platform can be measured since it is related to the experimentally measurable parameters of the micro-thermistor P_{b1}, P_{b2}, R_{b1}, R_{b2}, V_{b1}, and V_{b2}:

$$\frac{\alpha R_b}{\Omega} = \frac{(P_{b2} - P_{b1})}{(T_{b2} - T_{b1})} = \alpha R_b \frac{(P_{b2} - P_{b1})}{(R_{b2} - R_{b1})} = \alpha R_b \frac{\left(\frac{V_{b2}^2}{R_{b2}} - \frac{V_{b1}^2}{R_{b1}} \right)}{(R_{b2} - R_{b1})}$$

Since the micro-thermistor acts as a variable electrical resistance in the electrical circuit due to its non-zero temperature coefficient of resistance, the ohmic responsivity Ω represents the differential relation of the change of electrical resistance $dR_b = R_{b2} - R_{b1}$ of the micro-thermistor platform in response to an incremental change of heating power $dP_b = P_{b2} - P_{b1}$. In the present invention, it is desirable to have as large a temperature coefficient of resistance as possible for the micro-thermistor thermally sensitive thin film material in order to magnify the change of micro-thermistor electrical resistance in response to a change of heating power, and therefore improve device sensitivity. Ideally, the temperature coefficient of resistance should be larger than 0.5% per Kelvin ($\alpha > 0.005$).

As set forth in the above equation, the ohmic responsivity Ω of the micro-thermistor can be determined by a measurement of the incremental change of heating power

($dP_b = P_{b2} - P_{b1}$), and/or a measurement of the incremental change of temperature ($dT_b = T_{b2} - T_{b1}$), and/or a measurement of the incremental change of electrical resistance ($dR_b = R_{b2} - R_{b1}$), and/or a measurement of the incremental change of applied voltage ($dV_b = V_{b2} - V_{b1}$). Full temperature compensation for the gas pressure measurement method herein described can be obtained by keeping the incremental change of temperature ($dT_b = T_{b2} - T_{b1}$) constant during the measurements.

To cancel the temperature-dependency of the unknown power absorbed [10] [20] and dissipated [40] [50] [80] by the micro-thermistor platform [100], which depends mostly on the micro-thermistor temperature T_b, and to cancel the need for precise knowledge of the parameters (λ_{gas}, γ_{gas}, η, T_s, T_{env}, ε, d_s, d_e, β, h) of the system, it is sufficient to realize two measurements always at the same micro-thermistor temperatures (T_{b1}, T_{b2}) and to consider the difference of applied power dP_b [30] at those same two micro-thermistor temperatures. Assuming that the temperatures (T_{b1}, T_{b2}, T_s, T_{env}) and gas composition are kept constant during the two measurements, the conductivity terms G_{leg}, G_{rad}, and G_{conv} will be kept constant. The ohmic responsivity Ω will then be a function of pressure p only by virtue of the gas conductivity term $G_{gas} = G_{gas}(p)$:

$$\frac{\alpha R_b}{\Omega} = G_{leg} + G_{radiation} + G_{gas} + G_{conv} + \frac{dG}{dT_b}(T_b - T_s) = G_{gas} + \text{constant}$$

In this invention the preferred heating method consists of heating the micro-thermistor device with a binary-wave electrical excitation supplying an incremental amount of electrical heating power dP_b [30] to the micro-thermistor [100]. The binary-wave electrical excitation consists of a step-function voltage signal with a minimum voltage (V_1) followed by a maximum voltage (V_2), the difference between the minimum and maximum voltages corresponds to the amplitude of the binary-wave signal, $\Delta V = V_2$ -

V_1. The voltage V_b applied to the micro-thermistor depends on the electrical excitation V and on the transfer function f of the readout circuit, $V_b = f V$. The binary-wave signal generates an incremental amount of electrical heating power [30] applied to the micro-thermistor suspended platform [100], $dP_b = V_{b2}^2/R_{b2} - V_{b1}^2/R_{b1}$, leading to an incremental change of micro-thermistor electrical resistance, $dR_b = R_{b2} - R_{b1}$, where R_{b1} and R_{b2} are the electrical resistances of the micro-thermistor suspended platform at temperatures T_{b1} and T_{b2} respectively, and V_{b1} and V_{b2} are the voltages at the micro-thermistor when the voltage source [120] is at V_1 and V_2, respectively. By virtue of the relation between electrical resistance and temperature of the micro-thermistor, given by the temperature coefficient of resistance (TCR), the minimum voltage (V_1) of the binary-wave electrical excitation is adjusted so that the micro-thermistor resistance is at a predetermined value R_{b1} and the maximum voltage (V_2) of the binary-wave electrical excitation is adjusted so that the micro-thermistor resistance is at a predetermined value R_{b2}. The values of (R_{b1}, R_{b2}, dR_b, T_{b1}, T_{b2}) are thus constant and the measurements of (P_{b1}, P_{b2}, V_{b1}, V_{b2}) are done always at the same micro-thermistor temperatures T_b. The ohmic responsivity Ω of the suspended platform micro-thermistor can therefore be determined from $\Omega = dR_b/dP_b$ with minimization of the temperature dependencies of [10], [20], [40] [50] and [80].

Since the ohmic responsivity Ω of the suspended platform micro-thermistor is related to the thermal conductivity G of the micro-thermistor, and therefore to gas pressure p within the environment as mentioned previously, a measurement of ohmic responsivity will provide a measurement of gas pressure. The measurements must be made at thermal steady-state; since thermal steady-state is achieved typically after 10 msec or more the frequency ω of the binary-wave voltage source [120] must be below 100 Hertz for thermal steady-state to occur during the measurements.

The method for gas pressure measurement of the present invention thus consists in electrically exciting a suspended platform micro-thermistor sensor device with a binary-wave voltage source signal; and measuring the ohmic responsivity of the said suspended platform micro-thermistor sensor device; and determining gas pressure from said ohmic responsivity.

Figure 2 plots the relation between ohmic responsivity Ω and air pressure p for an exemplary micro-thermistor device. It can be seen that the ohmic responsivity varies as function of pressure in the range of air pressures between 10^{-4} Torr to 10^{4} Torr, thus providing gas pressure sensing capability over a wide dynamic range. Since the gas pressure sensing capability of the micro-thermistor gas pressure sensor extends from 10^{-4} Torr to 10^{4} Torr, the micro-thermistor gas pressure sensor can be used to monitor the pressure of a gas below and above atmospheric pressure. The sensor is not constrained to sensing gas pressure inside vacuum environments or packages. By a proper design of the distance d_s between the micro-thermistor platform [100] and the substrate [300], of the distance d_e between the micro-thermistor platform [100] and the window [500], of the surface area A and emissivity ε of the micro-thermistor platform [100], of the length of the suspending legs [200] and of the micro-thermistor temperature T_b, etc., the gas pressure sensing capability of the micro-thermistor gas sensor can be tuned below 10^{-4} Torr or above 10^{4} Torr. Low pressure sensing capability can be achieved, for example, by increasing the surface area A and decreasing the emissivity ε of the platform [100] and by increasing the length of the suspending legs [200]. High pressure sensing capability can be achieved, for example, by decreasing the distances d_s and d_e between the micro-thermistor platform [100] and the substrate [300] and window [500]. Gas pressure sensing tuning capabilities of the micro-thermistor gas sensor are not limited to these specific parameter changes.

Several micro-thermistor suspended platforms, with different physical characteristics such as the ones just mentioned, may be combined within a single readout circuit to provide sensing capability over a wider dynamic range than a single micro-thermistor suspended platform. For example, several micro-thermistor suspended platforms may be combined and tuned for measuring gas pressure at low pressure regimes, while several other micro-thermistor suspended platforms may be combined in the same readout circuit and tuned for measuring gas pressure at high pressure regimes; the plurality of micro-thermistor suspended platforms thus combined to provide sensing capability over an overall wider dynamic range. The plurality of micro-thermistor suspended platforms may be combined in series or in parallel with respect to the voltage source [120] along with load resistances, or load inductances, or load capacitances, or a combination thereof comprised in the same readout circuit [101].

Exemplary embodiments of the sensor apparatus:

Figure 3 and 4 show the schematics for exemplary embodiments of the micro-thermistor gas pressure sensor assembly of the present invention. The micro-thermistor gas pressure sensor assembly comprises 1) at least one suspended platform micro-thermistor sensor device [100] fabricated on a substrate [300] and exposed to the gas pressure of a given atmospheric environment [400], and 2) a readout electrical circuit [101] connected to the said suspended platform micro-thermistor sensor device [100], wherein said suspended platform micro-thermistor sensor device acts as a variable electrical resistance in the said readout electrical circuit [101], and 3) a binary-wave voltage source [120] connected to the said suspended platform micro-thermistor sensor device [100], and 4) ohmmeter [140].

In this invention, the ohmmeter [140] is an electrical element that measures the micro-thermistor [100] electrical resistance. A more accurate type of ohmmeter has an electronic circuit that passes a current (I_b) through the micro-thermistor resistance, and another circuit that measures the voltage (V_b) across the micro-thermistor resistance. Since the current I_b and voltage V_b at the micro-thermistor are related to the driving voltage V [120] and to the readout electrical circuit architecture [101], the micro-thermistor electrical resistance can be measured by probing the driving voltage V and the voltage V_L at some other load element (resistance, capacitance, or inductance) of the readout circuit. The readout electrical circuit [101] thus comprises at least one load resistance R_L (or a load capacitance, or a load inductance) that can be used to determine the micro-thermistor electrical resistance, and thus function as the ohmmeter [140] of the readout electrical circuit [101]. The ohmmeter load resistance can be the micro-thermistor electrical resistance itself, or any other electrical elements of the readout circuit either a resistance, a capacitance, or an inductance, or a combination thereof. The ohmmeter [140] is therefore either a R, a RC, a RL, or a RCL analog or digital electronic circuit part of the readout circuit [101].

The readout electrical circuit [101] comprises at least one load resistance acting as an ohmmeter [140], and may comprise other electrical resistances, capacitances and inductances. The readout circuit may be integrated on the substrate [300] by CMOS fabrication process, or be external to the substrate and made of standard electronics components electrically connected to the suspended platform micro-thermistor [100]. The micro-thermistor suspended platform [100] is a variable electrical resistance in the readout circuit [101] and is exposed to the gas pressure of a given atmospheric environment [400]. The rest of the readout circuit [101] may or may not be exposed to the gas pressure of the environment [400]. It will be appreciated by those skilled in the art that the exemplary embodiments shown in this invention relate to very simple readout circuits, easily integrated onto small CMOS platforms. Thus, the readout circuit [101] surface area may be as small as 1 mm^2 or smaller.

Figure 3 shows an exemplary readout circuit embodiment of the invention. The readout circuit [101] includes a voltage source [120] driving both a micro-thermistor device [100] and a load resistance [130]. The voltage source [120] provides a binary-wave voltage signal V [150] that can be adjusted in value and in amplitude (V_1, V_2, ΔV). The voltage V_L [160] at the load resistance [130] can be used to determine the resistance of the micro-thermistor [100], therefore the load resistance [130] acts as the ohmmeter [140] of the readout circuit [101]. The readout circuit [101] may be made of analog or digital electronics components or a combination of analog and digital electronics components. Given this circuit embodiment, the voltage V_b at the micro-thermistor [100] and the voltage V_L [160] at the load resistance [130] are given by the following transfer functions well known in the art:

$$V_b = V R_b / (R_L + R_b)$$
$$V_L = V R_L / (R_L + R_b)$$

The ohmic responsivity of the micro-thermistor device [100] can be determined using:

$$\Omega = dR_b/dP_b = (dR_b/dV_L)\ (dV_L/dV)\ (dV/dP_b) = (\Delta V_L / \Delta V)\ (R_L+R_b)^4 / 2V^2 R_b R_L$$

Where V is the average voltage value of the voltage signal [150], $V = (V_1 + V_2) / 2$, and R_b is the average electrical resistance of the micro-thermistor [100], $R_b = (R_{b1} + R_{b2})/2$. The ohmic responsivity Ω of the micro-thermistor device can be measured from the ratio between the voltage change ΔV_L at the load resistance [130,140] and the amplitude ΔV of the binary-wave voltage source [120] of the readout circuit [101]. Therefore, the electrical response ΔV_L of the ohmmeter [130,140] is proportional to the ohmic responsivity Ω of the micro-thermistor device [100], which is related to the gas pressure p inside the environment [400].

Cancellation of the temperature dependency of the thermal components [10], [20], [40], [50] and [80] can be achieved by keeping the voltages (V_{L1}, V_{L2},ΔV_L) at the load resistance always at the same predetermined values, while adjusting the binary-wave voltages (V_1, V_2,ΔV) to obtain the said voltages at the load resistance. The predetermined values of (V_{L1}, V_{L2},ΔV_L) are such that the minimum voltage (V_1) of the binary-wave electrical excitation is adjusted so that the micro-thermistor resistance is at a predetermined value R_{b1} (and the load voltage at a predetermined value V_{L1}) and the maximum voltage (V_2) of the binary-wave electrical excitation is adjusted so that the micro-thermistor resistance is at a predetermined value R_{b2} (and the load voltage at a predetermined value V_{L2}), where the difference of electrical resistance, $dR_b = R_{b2} - R_{b1} = \alpha R_b \, dT_b$, corresponds to a difference of temperature for the micro-thermistor, $dT_b = T_{b2} - T_{b1}$, of a few degrees Kelvin. The difference dR_b is thus a constant value and the measurements are done always at the same micro-thermistor temperatures and same ΔV_L. The incremental amount of electrical heating power [30] applied to the micro-thermistor suspended platform [100] is $dP_b = V_{b2}^2/R_{b2} - V_{b1}^2/R_{b1}$, where V_{b1} and V_{b2} are the voltage values at the micro-thermistor [100] related to V_1 and V_2 by virtue of the abovementioned transfer function, and the ohmic responsivity is determined by the ratio $\Omega = dR_b/dP_b$. Since the ohmic responsivity Ω of the micro-thermistor device [100] is related to its thermal conductivity G and to gas pressure p, the measurement of ohmic responsivity provides a measurement of gas pressure within the environment [400]. And since the load resistance [130] acts as the ohmmeter [140], the load voltage is identical to the ohmmeter voltage, $V_{ohm} = V_L$, and the ohmmeter electrical voltages ($V_{ohm1} = V_{L1}$, $V_{ohm2} = V_{L2}$, $\Delta V_{ohm} = \Delta V_L$) are kept constant at predetermined values, and the measurements are done always at the same micro-thermistor temperatures in order to cancel the temperature dependencies of the thermal components [10], [20], [40] [50] and [80].

Figure 4 shows another exemplary readout circuit embodiment of the invention. The readout circuit [101] includes a voltage source [120] driving both a micro-thermistor device [100] and a resistor bridge [210] comprising several resistors. The voltage source [120] provides a binary-wave voltage signal V [150] that can be adjusted in value and in amplitude (V_1, V_2, ΔV). The voltage V_G [220] at the bridge can be used to determine the resistance of the micro-thermistor [100], therefore the bridge voltage V_G [220] acts as the ohmmeter [140] of the readout circuit [101]. The readout circuit [101] may be made of analog or digital electronics components or a combination of analog and digital electronics components. Given this circuit embodiment, the voltage V_b at the micro-thermistor [100] and the voltage V_G [220] at the bridge are given by the following transfer functions well known in the art:

$$V_b = V R_b / (R_3 + R_b)$$
$$V_G = V (R_b / (R_3 + R_b) - R_2 / (R_1 + R_2))$$

The ohmic responsivity of the micro-thermistor device [100] can be determined using:

$$\Omega = dR_b/dP_b = (dR_b/dV_G) (dV_G/dV) (dV/dP_b) = (\Delta V_G / \Delta V) (R_L+R_b)^4 / 2V^2R_bR_L$$

Where V is the average voltage value of the voltage signal [150], $V = (V_1 + V_2) / 2$, and R_b is the average electrical resistance of the micro-thermistor [100], $R_b = (R_{b1} + R_{b2})/2$. The ohmic responsivity Ω of the micro-thermistor device can be measured from the ratio between the voltage change ΔV_G at the bridge [220] and the amplitude ΔV of the binary-wave voltage source [120] of the readout circuit [101]. Therefore, the electrical response ΔV_G of the ohmmeter [220,140] is proportional to the ohmic responsivity Ω of the micro-thermistor device [100], which is related to the gas pressure p inside the environment [400].

Cancellation of the temperature dependency of the thermal components [10], [20], [40], [50] and [80] can be achieved by keeping the voltages (V_{G1}, V_{G2},ΔV_G) at the bridge always at the same predetermined values, while adjusting the binary-wave voltages (V_1, V_2,ΔV) to obtain the said voltages at the bridge. The predetermined values of (V_{G1}, V_{G2}, ΔV_G) are such that the minimum voltage (V_1) of the binary-wave electrical excitation is adjusted so that the micro-thermistor resistance is at a predetermined value R_{b1} (and the bridge voltage at a predetermined value V_{G1}) and the maximum voltage (V_2) of the binary-wave electrical excitation is adjusted so that the micro-thermistor resistance is at a predetermined value R_{b2} (and the bridge voltage at a predetermined value V_{G2}), where the difference of electrical resistance, $dR_b = R_{b2} - R_{b1} = \alpha R_b\, dT_b$, corresponds to a difference of temperature for the micro-thermistor, $dT_b = T_{b2} - T_{b1}$, of a few degrees Kelvin. The difference dR_b is thus a constant value and the measurements are done always at the same micro-thermistor temperatures and same ΔV_G. The incremental amount of electrical heating power [30] applied to the micro-thermistor suspended platform [100] is $dP_b = V_{b2}^2/R_{b2} - V_{b1}^2/R_{b1}$, where V_{b1} and V_{b2} are the voltage values at the micro-thermistor [100] related to V_1 and V_2 by virtue of the abovementioned transfer function, and the ohmic responsivity is determined by the ratio $\Omega = dR_b/dP_b$. Since the ohmic responsivity Ω of the micro-thermistor device [100] is related to its thermal conductivity G and to gas pressure p, the measurement of ohmic responsivity provides a measurement of gas pressure within the environment [400]. And since the bridge [220] acts as the ohmmeter [140], the bridge voltage is identical to the ohmmeter voltage, $V_{ohm} = V_G$, and the ohmmeter electrical voltages ($V_{ohm1} = V_{G1}$, $V_{ohm2} = V_{G2}$, $\Delta V_{ohm} = \Delta V_G$) are kept constant at predetermined values, and the measurements are done always at the same micro-thermistor temperatures in order to cancel the temperature dependencies of the thermal components [10], [20], [40], [50] and [80].

The invention is not limited to these specific readout circuit embodiments and may show different circuit architectures comprising electrical resistances, capacitances and inductances, connected in such a way as to generate different transfer functions with or without electrical gain, and to provide a measurement of the ohmic responsivity of the micro-thermistor suspended platform [100].

Since the ohmic responsivity of the micro-thermistor suspended platform [100] is related to gas pressure, the micro-thermistor gas pressure sensor assembly of the present invention becomes calibrated by measuring and specifying the parametric relation between the ohmic responsivity Ω of the micro-thermistor suspended platform [100] and the gas pressure p within the environment [400]. Equivalently, the micro-thermistor gas pressure sensor assembly of the present invention becomes calibrated by measuring and specifying the parametric relation between the ohmmeter electrical voltage difference ΔV_{ohm} and the gas pressure p within the environment [400].

The relation between Ω and p for the micro-thermistor gas pressure sensor are fundamentally linked to the relation between the thermal conductivity G of the micro-thermistor device and the gas pressure p.

$$\frac{\alpha R_b}{\Omega} = G_{leg} + G_{radiation} + G_{gas} + G_{conv} + \frac{dG}{dT_b}(T_b - T_s)$$

If the measurements are performed always at the same two micro-thermistor suspended platform temperatures T_{b1} and T_{b2}, the relation becomes:

$$\frac{\alpha R_b}{\Omega} = G_{gas} + \text{constant} = \frac{\beta \cdot A}{\frac{ds}{\lambda_{gas_s}} + \frac{1}{\gamma_{gas} \cdot p}} + \frac{k \cdot \beta \cdot A}{\frac{de}{\lambda_{gas_e}} + \frac{1}{\gamma_{gas} \cdot p}} + \text{constant}$$

Assuming no temperature dependence, the variation of thermal conductivity G of the micro-thermistor device with pressure can be reduced to a 5-parameter polynomial relation that cancels the need for precise knowledge of the parameters (λ_{gas}, γ_{gas}, η, T_s, T_{env}, ε, d_s, d_e, β, h) of the system. If a relation between ohmic responsivity Ω and gas pressure p is sought, then we obtain a relation where the ohmic responsivity Ω is commensurate with the gas pressure p:

$$\alpha R_b / \Omega = X1 + X2 / (X3+p^{-1}) + X5 / (X4+p^{-1}).$$

Where: $X1 = G_{leg} + G_{rad} + G_{conv} + dG/dT_b (T_b-T_s)$, $X2 = \gamma\beta A$, $X3 = \gamma d_s/\lambda$, $X4 = \gamma d_e/\lambda$ and $X5 = k\gamma\beta A$. Since the ohmic responsivity Ω is related to the experimentally measurable parameters of the micro-thermistor (P_{b1}, P_{b2}, R_{b1}, R_{b2}, V_{b1}, V_{b2}) and to the experimentally measurable parameters of the readout circuit (R_L, V_{ohm}, etc.), the 5-parameter polynomial relation can also relate to those measurable parameters. For example, if a relation between ohmmeter electrical voltage difference ΔV_{ohm} and gas pressure p is sought, then we obtain a relation where the ohmmeter electrical voltage ΔV_{ohm} is commensurate with the gas pressure p:

$$(\Delta V / \Delta V_{ohm})\, 2\alpha\, V^2 R_b^2 R_L / (R_L+R_b)^4 = X1 + X2 / (X3+p^{-1}) + X5 / (X4+p^{-1}).$$

This relation is valid for the embodiments shown in figures 3 and 4, and the left hand side of the relation may be different for other readout circuit architectures having different voltage transfer functions, and the relation between p and ΩV_{ohm} can be reduced and normalized to a 5-parameter polynomial relation.

Therefore, calibrating the micro-thermistor gas pressure sensor made of a micro-thermistor device [100] and readout circuit [101] requires at least 5 different parameters, because the mathematical relation between gas pressure and ohmic responsivity comprises at least 5 different parameters; X1, X2, X3, X4 and X5. These parameters can be measured by performing 5 thermal conductivity measurements (or 5 ohmic responsivity measurements) at 5 different pressures, from which the parameters can be determined using standard fitting routines. These parameters depend on several factors such as temperature, gas composition and micro-thermistor physical characteristics, as listed in the table below. Therefore, whenever the parametric relation of a single sensor is extended to other sensors, several assumptions are implicitly made as described in Table 1. If the assumptions are valid, a same 5-parameter polynomial relation can be applied to a plurality of micro-thermistor gas pressure sensors of the same physical characteristics. Therefore, if the assumptions are valid, the same ohmic responsivity applies to a plurality of suspended platform micro-thermistor gas pressure sensors of the same physical characteristics.

Parameter	**Form**	**Dependencies**
X1	$X1 = G_{leg} + G_{rad} + G_{conv} + dG/dT_b (T_b - T_s)$	Micro-thermistor temperature, substrate temperature, environment temperature, packaging environment, leg conduction, micro-thermistor emissivity, micro-thermistor surface area.
X2	$X2 = \gamma\beta A$	Gas composition, micro-thermistor surface area.
X3	$X3 = \gamma d_s/\lambda$	Gas composition, substrate temperature, micro-thermistor distance to substrate.

X4	$X4 = \gamma d_e/\lambda$	Gas composition, environment temperature, micro-thermistor distance to environment, packaging environment.
X5	$X5 = k\gamma\beta A$	Gas composition, micro-thermistor surface area, environment temperature, substrate temperature.

Table 1: Parameters of the abovementioned 5-parameter polynomial relation.

In the present invention, the method for gas pressure measurement thus consists in electrically exciting a suspended platform micro-thermistor sensor device [100] with a binary-wave voltage source signal [120], and 2) measuring the ohmic responsivity of the said suspended platform micro-thermistor sensor device using an ohmmeter, wherein said ohmmeter has an electrical response proportional to said ohmic responsivity, and 3) determining gas pressure p from said ohmic responsivity Ω, wherein the ohmic responsivity is related to the micro-thermistor thermal conductivity and to gas pressure. Gas pressure p is determined by the abovementioned 5-parameter polynomial relation relating pressure p with ohmic responsivity Ω. Equivalently, gas pressure p is determined by the abovementioned 5-parameter polynomial relation relating pressure p with the ohmmeter electrical voltage difference ΔV_{ohm}.

The above-mentioned 5-parameter polynomial relation is valid under the assumption of no temperature dependence. However, the temperatures inside the environment may vary with time due to thermal fluctuations, creating undesirable effects on the sensor calibration as most of the parameters of the parametric relation depend on temperature because they involve $G_{rad} = G_{rad}(T_b,T_s,T_{env})$ and $G_{gas} = G_{gas}(T_b,T_s,T_{env})$.

The effects of a variation of (T_b,T_s,T_{env}) and the deviations from an ideal 5-parameter parametric relation can be determined by MonteCarlo simulation as plotted in figure 5. The plot shows the 1σ statistical error on the pressure measurement under a temperature fluctuation of 1K (1σ) for T_b and 10K (1σ) for (T_s,T_{env}). This statistical error on the pressure measurement is with respect to a calibration done with a 5-parameter parametric relation under non-fluctuating temperatures. The relative errors on pressure measurements are typically below 10% between 10^{-2} Torr to 10^3 Torr of air pressure. Therefore, the micro-thermistor gas pressure sensor of the present invention provides gas pressure sensing capability with good immunity to temperature fluctuations over a wide dynamic range. Further immunity to temperature fluctuations may be obtained by coupling thermally the substrate [300] of the gas pressure sensor assembly with a temperature controller, such as a thermo-electric cooling device.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.

FIG. 1

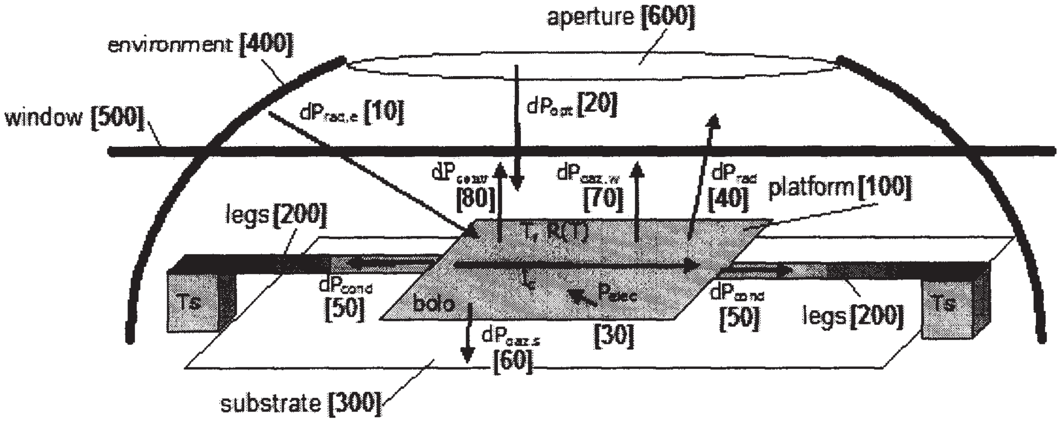

aperture [600]
environment [400]
window [500]
$dP_{rad,e}$ [10]
dP_{opt} [20]
dP_{conv} [80]
$dP_{conv,w}$ [70]
dP_{rad} [40]
platform [100]
legs [200]
T, R(T)
Ts
dP_{cond} [50]
I_c
P_{elec}
bolo
dP_{cond} [50]
legs [200]
Ts
$dP_{conv,s}$ [60]
[30]
substrate [300]

FIG. 2

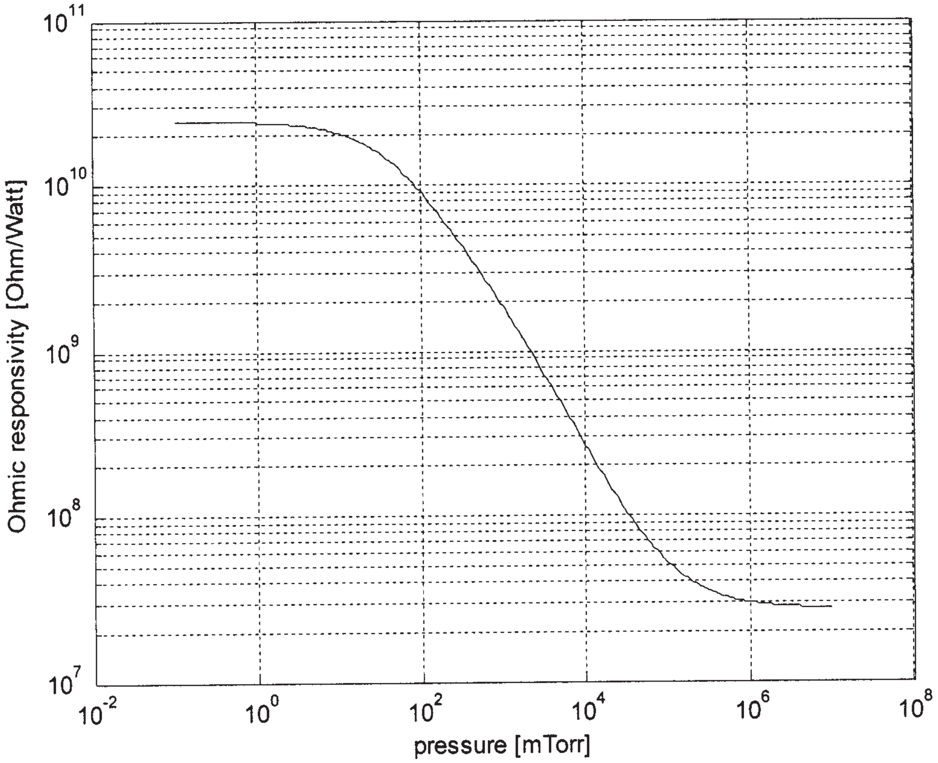

10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
Ohmic responsivity [Ohm/Watt]
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
pressure [mTorr]

FIG. 3

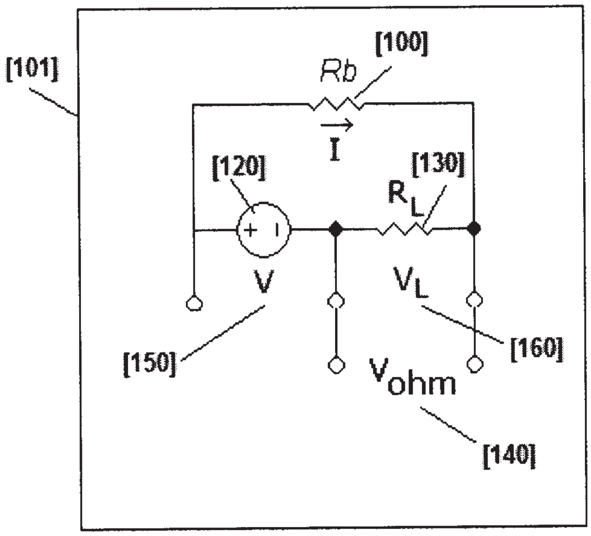


FIG. 4

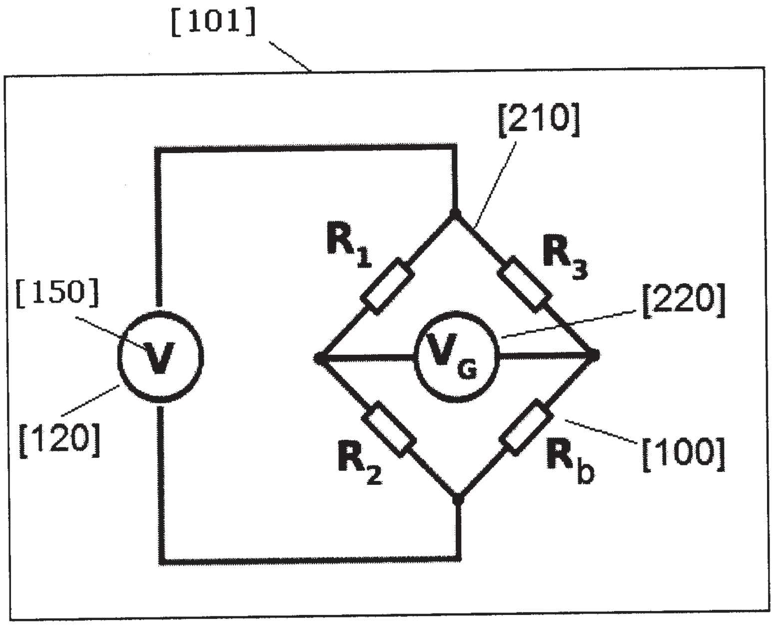
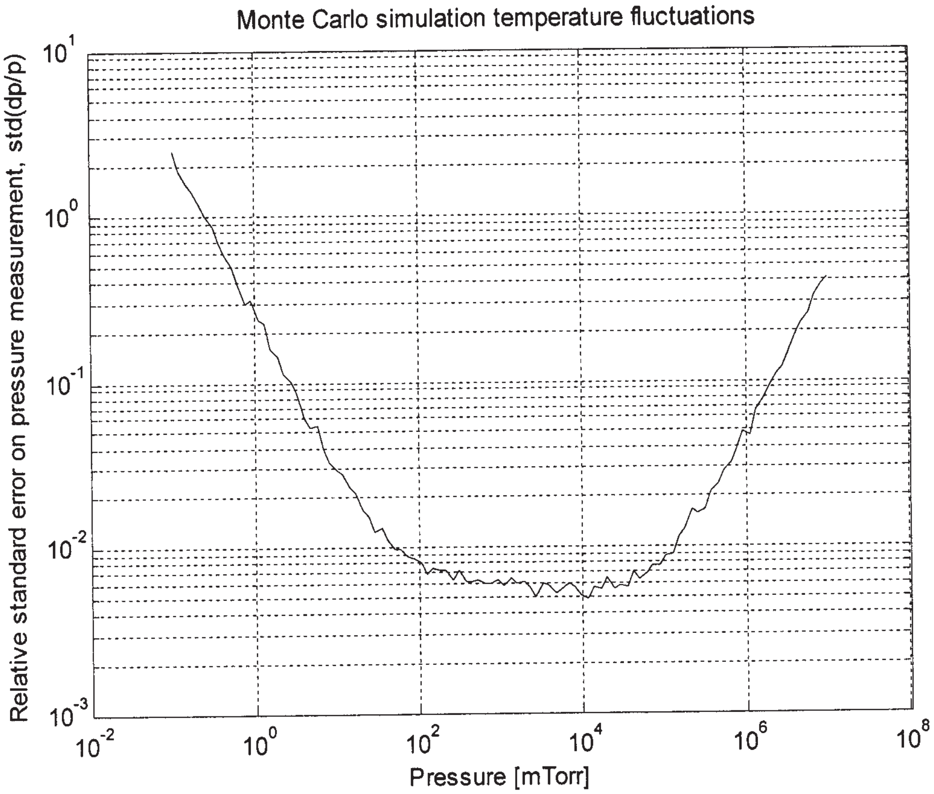
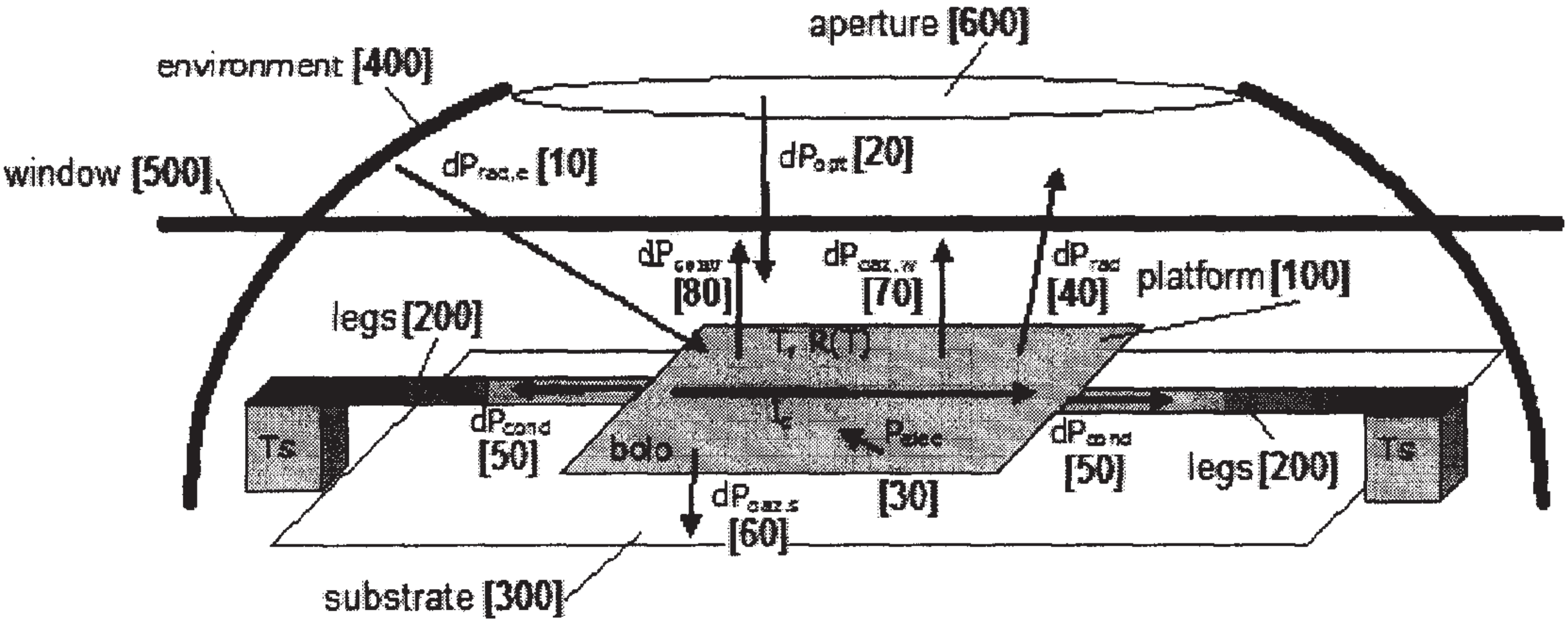


FIG. 5


Monte Carlo simulation temperature fluctuations
Relative standard error on pressure measurement, std(dp/p)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^0
10^2
10^4
10^6
10^8
Pressure [mTorr]



aperture [600]
environment [400]
window [500]
$dP_{rad,e}$ [10]
dP_{opt} [20]
dP_{conv} [80]
$dP_{conv,w}$ [70]
dP_{rad} [40]
platform [100]
legs [200]
T, R(T)
I_c
bolo
P_{elec}
dP_{cond} [50]
dP_{cond} [50]
[30]
$dP_{conv,s}$ [60]
legs [200]
Ts
Ts
substrate [300]