GAS COMPOSITION SENSING USING CARBON NANOTUBE ARRAYS

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Field of Classification Search
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See application file for complete search history.

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A method and system for estimating one, two or more unknown components in a gas. A first array of spaced apart carbon nanotubes ("CNTs") is connected to a variable pulse voltage source at a first end of at least one of the CNTs. A second end of the at least one CNT is provided with a relatively sharp tip and is located at a distance within a selected range of a constant voltage plate. A sequence of voltage pulses \( \{ V(t_n) \} \) at times \( t = t_1, \ldots, t_N \) is applied to the at least one CNT, and a pulse discharge breakdown voltage is estimated for one or more gas components. The estimated pulse discharge breakdown threshold voltage is compared with known threshold voltages for candidate gas components to estimate whether at least one candidate gas component is present in the gas. The procedure can be repeated at higher pulse voltages to estimate a second component present in the gas.

Claims, 4 Drawing Sheets
**Fig. 3A**

- $I(t; k)$
- $I_{br}(2)$
- $I_{br}(1)$
- $k = 1$
- $t_{N1}$
- $t_{N2}$

**Fig. 3B**

- $e$
- $e_{br}(2)$
- $e_{br}(1)$
- $k = 1$
- $t_{N1}$
- $t_{N2}$
Provide array of CNTs in chamber, with at least one CNT having first CNT end connected to a first variable voltage source and having a second CNT end spaced apart a distance \( d(\geq 0) \) from a constant voltage source.

Provide gas \( G \) in chamber adjacent to the CNT second end.

Provide an estimated threshold discharge voltage value \( V(k;\text{thr}) \) for each of \( K \) candidate gas components \( (K \geq 1) \).

Measure or provide a threshold discharge voltage value \( V(\text{meas};\text{thr}) \) for the gas \( G \).

Compute an error \( \varepsilon(k) \), depending on a difference between \( V(k;\text{thr}) \) and \( V(\text{meas};\text{thr}) \) for each candidate gas component \( k = 1, \ldots, K \).

(1) \( \varepsilon(k_1), \varepsilon(k_1;\text{thr}) \) and (2) \( \varepsilon(k_1) = \min \varepsilon(k) \) for at least one index value \( k, (1 \leq k \leq K) \).

Note that candidate gas component no. \( k \), is (likely to be) present in gas \( G \).

Terminate procedure (optional).

Fig. 4A
Identify a new measured threshold discharge voltage value $V(\text{new}; \text{meas}; \text{thr}) > V(\text{meas}; \text{thr})$

Replace $V(\text{meas}; \text{thr})$ by $V(\text{new}; \text{meas}; \text{thr})$

Fig. 4B
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GAS COMPOSITION SENSING USING CARBON NANOTUBE ARRAYS

ORIGIN OF THE INVENTION

This invention relates to determination of gas composition, using carbon nanotubes to provide pulse voltage discharges.

BACKGROUND OF THE INVENTION

Few sensors are available to detect inert gases. Conventional inert gas analysis tools primarily rely upon infrared (IR) spectroscopy, mass spectroscopy (MS) and/or thermal conductivity measurements. Thermal conductivity sensors are available for fixed and portable instruments, but this technique is not suitable for measuring extremely low levels of a gas (e.g., less than 1 percent by volume resolution), and the technique has difficulties when the target gas has a thermal conductivity close to that of a background gas. For example, measurement of oxygen in air is not feasible, because the two gases have essentially the same thermal conductivity.

IR spectroscopy is often used to measure carbon dioxide in air, or methane in carbon dioxide, as found in sewage digestor and coal gasification plants. This technique is superior to thermal conductivity sensing in accuracy and resolution, but use of IR is more expensive due to the complex optics and signal processing required. A MS-based sensor can be used to detect presence of an inert gas, but this technique is expensive and heavy and time consuming and is not suitable for in situ measurements. Fourier transform IR and MS techniques require bulky, heavy instruments and/or high temperature operation, and consumption of electrical power is very large.

What is needed is a relatively lightweight and small sensor for inert gases that consumes a relatively small amount of power and that provides measurements that are as accurate as the conventional approaches. Preferably, this sensor should be able to detect and identify presence of one, two or more gases, some or all of which may be inert.

SUMMARY OF THE INVENTION

These needs are met by the invention, which provides an electrical discharge sensor that measures a specific gas breakdown voltage associated with each gas present. In one embodiment, a method for practicing the invention includes the following processes: (1) a first array of spaced apart carbon nanotubes ("CNTs") is provided in a closed chamber, at least one CNT in the first array being attached at a first end to a first variable voltage source, and having a relatively sharp CNT tip at a second end of the at least one CNT, where the second end of the at least one CNT in the first array is located at a distance in a range 10–200 μm from a plate having substantially constant voltage (V=V0); (2) a gas, having at least one unknown gas component and having a pressure in a range 10−3–760 Torr, is provided in the chamber; (3) a first sequence of voltage pulses, having known voltages V(t1), V(t2), …, V(tN1) (preferably with monotonically increasing magnitudes) at times t1, t2, …, tN1, where N1≥2 and Δt=tN1−t1 is at least equal to a selected gas recovery time; (4) a first pulse discharge breakdown threshold voltage V(1; thr) is estimated from a comparison of at least one of (i) three current values I(t1), I(t2), and I(tN1) (ml≥1; n2≥1) with each other, and (ii) three cumulative electrical charge values e(t1), e(t2), and e(tN1) with each other. For example, the slope of the curve I(t; 1) or the curve e(t; 1), extended to continuous values of time t, may abruptly increase or otherwise change as the discharge breakdown threshold, V=V(1; thr) is reached or exceeded.

Two or more CNT arrays, spaced apart from each other, can be pulsed at different voltages V(t1), V(t2), …, V(tN1) at spaced apart times (i) to determine more quickly the breakdown threshold voltage of an unknown gas component that is present, by bracketing the breakdown threshold voltage, or (ii) to independently determine pulse discharge breakdown threshold voltages for two or more distinct gas components that may be simultaneously present. Because the exposed tips of the CNTs are relatively sharp, the amount of power required at a given voltage level is less than would be required for tips that are blunter and/or broader, and (ii) the pulse discharge breakdown threshold voltage for a given gas can be determined more precisely. The CNTs used here are preferably multi-wall CNTs ("MWNTs," including two or more concentric, roughly cylindrical layers) and/or carbon nanofibers ("CNFs," including two or more concentric, roughly conical layers).

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1 and 2 illustrate two systems for practicing the invention, using one array and two independently addressable arrays of CNTs.

FIGS. 3A and 3B graphically illustrate variation of measured electrical current and cumulative electrical charge, respectively, associated with variation of a pulsed voltage delivered to a CNT array in FIG. 1 or FIG. 2.

FIGS. 4A/4B are a flow chart of a procedure for practicing the invention.

DESCRIPTION OF BEST MODES OF THE INVENTION

FIG. 1 illustrates a system 11 for practice one embodiment of the invention. The system 11 includes first and second plates, 12A and 12B, where the first plate 12A is connected to spaced apart CNTs at a first CNT array end and is connected to a source 14 of variable pulsed voltage; and the second plate 12B is connected to a source 15 of, or is maintained at, substantially constant voltage V0 (which may be, but need not be, zero voltage). For definiteness, it is assumed here that the voltages associated with the first plate 12A are positive; if the voltages of the first plate are negative, V(t) should be replaced by −V(t) in the following discussion.

The first plate 12A or the second plate 12B is also connected to a current measurement device 16, for example, an ammeter or a time integrated or cumulative electrical charge meter (referred to collectively herein as a "meter"). Optionally, each of two or more spaced apart CNT arrays may be connected, through a split plate 12A-1 and 12A-2, as illustrated in FIG. 2 (or, optionally, through a single first plate, as
in FIG. 1, to the pulsed voltage sources, 14-1 and 14-2, where a voltage pulse of independent and controllable magnitude can be delivered to each of the (split) plates independently. The first and second plates, 12A and 12B, in FIG. 1 are separated by an insulating spacer 17. Similar insulating spacers may be used to electrically isolate the (split) plates 12A-1 and 12A-2 from each other and from the plate 12B in FIG. 2.

In FIG. 1, and similarly in FIG. 2, a gas G of unknown composition is introduced into a region between the CNT array(s) 13 (or the arrays 13-1 and 13-2) and the second plate 12B. A sequence of voltage pulses \( V(n; i); 1 \) (spaced apart in time) of increasing magnitude is delivered by the voltage pulse source 14 to the first plate 12A in FIG. 1 (\( n=1, 2 \ldots, N1 \)). At the voltage \( V(n; i); 1 \), no discharge breakdown occurs in the gas, but at the next voltage in the sequence, \( V(n_{break}; i); 1 \), discharge breakdown occurs in the gas. This indicates that the gas discharge breakdown voltage magnitude is greater than \( V(n_0); 1 \) but is not larger than \( V(n_{break}; i); 1 \). This smaller pulse voltage interval, \( V(n_{break}; i); 1 \leq V < V(n_0); 1 \), can be further explored by delivering a sequence of voltage pulses with magnitudes increasing from \( V(n_{break}; i); 1 \) to \( V(n_{break}+1); 1 \) to obtain an estimate of the actual pulse discharge breakdown threshold voltage for a first component of the gas. The slope of the curve \( I(t; k) \) or \( e(t; k) \) \((k=1, 2, \ldots, N1)\) abruptly increases as each pulse discharge breakdown threshold voltage \( V(k; thr) \) is reached or exceeded. A second component of the gas with a higher pulse discharge breakdown threshold voltage, if present, can be determined in a similar manner, using the system 11 shown in FIG. 1 or using the split plate system 21 shown in FIG. 2.

Presence of pulse discharge breakdown in a gas may be determined in the following manner, using an ammeter or cumulative charging sensing device connected between the first and second plates, 12A and 12B, in FIG. 1. Contemporaneous with delivery of each voltage pulse to the first plate 12A, an electrical current value \( I(t; k) \) or a peak electrical current value \( I_{peak}(k) \) is measured between the first and second plates, 12A and 12B. Discharge occurs in the gas for delivery of a given voltage pulse if and only if \( I(t; k) \geq I(k; thr) \) or \( I_{peak}(k) \geq I(k; thr) \) or if the slope of the curve \( I(t; k) \) abruptly increases, where \( I(k; thr) \) is a selected breakdown threshold current value, as illustrated graphically in FIG. 3. Alternatively, where a cumulative charging sensing device is connected between the first and second plates, 12A and 12B, in FIG. 1, discharge breakdown occurs in the gas for delivery of a given voltage pulse if and only if the time integral \( I(t; k)dt \), representing cumulative electrical charging \( e(t; k) \), for a given time interval including time of delivery of the voltage pulse, is greater than a threshold electrical charge value \( e(k; thr) \) or the slope of the curve \( e(t; k) \) abruptly increases, as illustrated in FIG. 3B.

In each of FIGS. 3A and 3B, the measured current \( I(t; k) \) and/or the cumulative electrical charge measured \( e(t; k) \), respectively, would be expected to continue to increase as the pulse voltage delivered increases beyond the pulse discharge breakdown threshold voltage \( V(k; thr) \). If a second gas component is present that has a higher (preferably, substantially higher) associated pulse discharge breakdown threshold voltage, \( V2; thr \), the measured current \( I(t; 2) \) or the measured cumulative electrical charge \( e(t; 2) \) continues to increase with a certain slope as \( V \) increases above \( V1; thr \) toward, but below, \( V2; thr \). Above \( V=V(2; thr) \), the slope of the curve \( I(t; 2) \) or the slope of a curve \( V(t; 2) \) abruptly increases, as illustrated in FIGS. 3A and 3B, respectively, indicating presence of a second gas component with a pulse discharge breakdown threshold voltage \( V(2; thr) \) is determined in a manner similar to that for the voltage \( V(1; thr) \). This approach can be used to estimate a discharge breakdown voltage for two or more gas components, if the pulse discharge breakdown threshold voltages are spaced apart sufficiently.

FIGS. 4A/4B is a flow chart of a procedure for estimating a first or nth component of a gas. In step 41, a first array of spaced apart carbon nanotubes ("CNTs") is provided in a closed chamber, at least one CNT in the first array being attached at a first CNT end to a first variable voltage source and having a relatively sharp CNT tip at a second end of the at least one CNT, where the second end of the at least one CNT in the first array is located at a distance in a range 10-200 \( \mu \)m from a substantially constant voltage plate. Each CNT array preferably has a diameter of at least 20 \( \mu \)m, more preferably in a range of 20-50 \( \mu \)m. The array diameter may be as small as 1-5 \( \mu \)m, or smaller if desired. Any two CNT arrays are preferably spaced apart by a distance of at least 200 \( \mu \)m, preferably at least 500 \( \mu \)m. In step 42, having a least one unknown gas component and having a pressure in a range of 10\(^{-2}\) - 760 Torr, is provided in the chamber.

In step 43, an (estimated) threshold discharge voltage value \( V(k; thr) \) \((k=1, \ldots, K)\) is provided for each of \( K \) candidate gas components identified, for example, by use of a slope change method such as illustrated in FIGS. 3A/3B. In step 44, a threshold discharge voltage value \( V(meas; thr) \) is measured or otherwise provided for at least one component of the gas G. In step 45, errors \( \epsilon(k) \) including difference values are computed, for example,

\[
\epsilon(k)=\frac{V(meas; thr)-V(k; thr)}{V(k; thr)}
\]
The gas sensor disclosed here can be operated at room temperature, or at any other reasonable temperature, and at any reasonable temperature, such as atmospheric pressure or moderately lower. Where the gas pressure in the chamber is p and the tip-to-constant voltage plate distance is d, the product pd will approximately characterize the pulse breakdown threshold voltage where d is no more than 1–3 mean free paths at the gas concentration provided. For example, where an iron cathode is provided, helium, argon and air require minimum pulse voltages of 150 V, 265 V and 330 V, respectively, p at product values of 2.5 Torr-cm, 1.5 Torr-cm and 0.57 Torr-cm (A. Von Engel, *Ionized Gases*, 1955, p. 173). The proper distance d should be determined or "tuned" for operation at the pressure p chosen, such as p=1 Torr. One distance range that works, not necessarily optimally, is d=50–100 μm.

Approximate values for pulse discharge breakdown threshold voltages for different gases and gas combinations have been preliminarily estimated, using this approach:

\[
V(1; \text{thr})=164 \text{ V for He}, \\
V(2; \text{thr})=245 \text{ V for Ar}, \\
V(3; \text{thr})=345 \text{ V for NH}_3. 
\]

What is claimed is:

1. A method for estimating the composition of a gas, the method comprising:
   - providing a first array of spaced apart carbon nanotubes ("CNTs") in a closed chamber, at least one CNT in the first array being attached at a first CNT end to a first variable voltage source and having a relatively sharp CNT tip at a second end of the at least one CNT, the first end of the at least one CNT in the first array is located at a distance in a range of about 10–200 μm from a substantially constant voltage plate;
   - providing a gas, having at least one unknown gas component and having a pressure in a range of about 10⁻¹⁻⁷ Torr, in the chamber;
   - applying first voltage pulses, having voltages \( V(t_{n1}); l > V(0) \), at a sequence of times \( t_{n1} \) \((n1=1, \ldots, N1; N1 \geq 3) \) to the at least one CNT in the first array, and measuring at least one of a first associated electrical current \( I(t_{n1}); l \) and a first cumulative electrical charge \( e(t_{n1}); l \) that passes between the at least one CNT in the first array and the substantially constant voltage plate, for each of the N1 voltages \( V(t_{1}); V(t_{2}); \ldots, V(t_{N1}); 1 \);
   - estimating a first measured pulse discharge breakdown threshold voltage \( V(\text{meas}; \text{thr}) \) from a comparison of at least one of (i) three electrical current values \( I(t_{n1}; l) \); \( I(t_{n1+m1}; l) \); \( I(t_{n1+m2}; l) \) with each other; and (ii) three cumulative electrical charge values \( e(t_{n1+m1}; l) \); \( e(t_{n1}; l) \); \( e(t_{n1+m2}; l) \) with each other, for selected numbers \( m1 \geq 1 \) and \( m2 \geq 1 \);
   - providing a threshold discharge voltage value \( V(k; \text{thr}) \) for each of K candidate gas components, numbered \( k=1, \ldots, K \); computing an error \( e(k) \) \((k=1, \ldots, K) \) that depends upon a difference between the measured breakdown threshold voltage \( V(\text{meas}; \text{thr}) \) and the threshold discharge voltage \( V(k; \text{thr}) \);
   - when the error \( e(k) \), for \( k=k1 \), satisfies at least one of the conditions (1) \( e(k1) \leq e(k1; \text{thr}) \), where \( e(k1; \text{thr}) \) is a selected threshold error, and (2) \( e(k1; \text{thr})=\min_{k \geq 2} e(k; \text{thr}) \), interpreting this satisfaction as indicating that the gas component no. \( k=k1 \) is likely to be present in the gas \( G \); and
   - when no candidate gas component no. \( k=k1 \), exists that satisfies at least one of the conditions (1) \( e(k1) \leq e(k1; \text{thr}) \) and (2) \( e(k1) \leq \min_{k \geq 2} e(k; \text{thr}) \), interpreting this satisfaction as indicating that none of the gas components no. \( k=1, \ldots, K \) is likely to be present in the gas \( G \).

2. The method of claim 1, further comprising:
   - providing said sequence \( \{V(t_{n1}); l\}_1 \) of said voltages as a monotonically increasing sequence satisfying \( V(1); 1 < V(2); 1 < \ldots < V(t_{n1}); 1 \), with \( V(t_{1}); 1 \) less than a breakdown voltage threshold for said gas; and interpreting occurrence of the simultaneous conditions (i) \( I(t_{n1}); l < I(l; \text{thr}) \), where \( I(l; \text{thr}) \) is a selected threshold current value, and (ii) \( I(t_{n1-1}); l \geq I(l; \text{thr}) \) and (iii) \( V(t_{n1-1}); 1 \geq V(t_{n1}); 1 \) as indicating that a component in said gas is present having a pulse discharge breakdown threshold voltage \( V(1; \text{thr}) \), satisfying \( V(t_{1}); 1 < V(1); 1 \geq V(1; \text{thr}) \).

3. The method of claim 1, further comprising choosing said error \( e(k) \) to be \( e(k)=A \cdot V(\text{meas}; \text{thr})-V(k; \text{thr}) \), where \( A \) is a selected positive value.

4. The method of claim 1, further comprising:
   - providing said sequence \( \{V(t_{n1}); l\}_1 \) of said voltages as a monotonically decreasing sequence satisfying \( V(1); 1 > V(2); 1 > \ldots > V(t_{n1}); 1 \), with \( V(t_{1}); 1 \) greater than a breakdown voltage threshold for said gas; and interpreting occurrence of the simultaneous conditions (i) \( I(t_{n1}); l > I(l; \text{thr}) \), where \( I(l; \text{thr}) \) is a selected threshold current value, and (ii) \( I(t_{n1-1}); l \leq I(l; \text{thr}) \) and (iii) \( V(t_{n1-1}); 1 > V(t_{n1}); 1 \) as indicating that a component in said gas is present having a pulse discharge breakdown threshold voltage \( V(1; \text{thr}) \), satisfying \( V(t_{1}); 1 > V(1); 1 \geq V(1; \text{thr}) \).

5. The method of claim 1, further comprising:
   - providing said sequence \( \{V(t_{n1}); l\}_1 \) of said voltages as a monotonically increasing sequence satisfying \( V(1); 1 < V(t_{2}); 1 < \ldots < V(t_{n1}); 1 \) and \( V(t_{n1}); 1 \); and interpreting occurrence of the simultaneous conditions (i) \( e(t_{n1}); l < e(l; \text{thr}) \), where \( e(l; \text{thr}) \) is a selected threshold electrical charge value, and (ii) \( e(t_{n1}); l \geq e(l; \text{thr}) \) and (iii) \( V(t_{n1}); 1 = V(t_{n1+1}); 1 \) as indicating that a component in said gas is present having a breakdown voltage \( V(1; \text{thr}) \) satisfying \( V(t_{1}); 1 < V(1); 1 < V(t_{n1+1}); 1 \).

6. The method of claim 1, further comprising:
   - providing said sequence \( \{V(t_{n1}); l\}_1 \) of said voltages as a monotonically increasing sequence satisfying \( V(t_{1}); 1 > V(t_{2}); 1 > \ldots > V(t_{n1}); 1 \) and \( V(t_{n1}); 1 \); and interpreting occurrence of the simultaneous conditions (i) \( e(t_{n1}); l > e(l; \text{ thr}) \), where \( e(l; \text{thr}) \) is a selected threshold electrical charge value, and (ii) \( e(t_{n1}); l \geq e(l; \text{thr}) \) and (iii) \( V(t_{n1}); 1 < V(t_{n1+1}); 1 \) as indicating that a component in said gas is present having a breakdown voltage \( V(1; \text{ thr}) \) satisfying \( V(t_{1}); 1 < V(t_{n1+1}); 1 \).

7. The method of claim 1, further comprising:
   - providing said sequence \( \{V(t_{n1}); l\}_1 \) of said voltages as a monotonically increasing sequence satisfying \( V(t_{1}); 1 > V(t_{2}); 1 \); and interpreting occurrence of the simultaneous conditions (i) \( e(t_{n1}); l > e(l; \text{ thr}) \), where \( e(l; \text{ thr}) \) is a selected threshold electrical charge value, and (ii) \( e(t_{n1}); l \leq e(l; \text{ thr}) \) and (iii) \( V(t_{n1}); 1 = V(t_{n1+1}); 1 \) as indicating that a component in said gas is present having a breakdown voltage \( V(1; \text{ thr}) \) satisfying \( V(t_{1}); 1 < V(t_{n1+1}); 1 \).

8. The method of claim 1, further comprising:
   - providing a second spaced apart array of CNTs in said chamber, each CNT in the second array being attached at a first end to said variable voltage source and having a relatively sharp CNT tip at a second end that is directed toward said constant voltage plate, where the second end.
of at least one CNT in the second array is located at a distance in a range of about 10–200 µm from said plate, to provide a second pulse voltage that is independent of said first pulse voltage provided by said variable voltage source, and where the second CNT array is spaced apart from the first CNT array by a distance of at least 50 µm; and

applying second pulse voltages, having known voltages, \( V(t_{n2}; k) \), to each of at least one of a current meter and a cumulative electrical charge meter (collectively referred to as a “meter”), for each of at least two voltages \( V(t_{n2} - 3; 2) \) and \( V(t_{n2}; 2) \) and estimating a second pulse discharge breakdown threshold voltage \( V(2; \text{thr}) \) from a comparison of at least one of (i) three electrical current values \( I(t_{n2}; 2) \), \( I(t_{n2}; 2) \), and \( I(t_{n2}; m4) \) with each other, and (ii) three cumulative electrical charge values \( e(t_{n2}; 2) \), \( e(t_{n2+1}; 2) \), and \( e(t_{n2+m4}; 2) \) with each other, where \( m3 \geq 1 \) and \( m4 \geq 1 \).

9. A system for estimating the composition of a gas, the system comprising:

- a first array of spaced apart carbon nanotubes (“CNTs”) in a closed chamber, at least one CNT in the first array being attached at a first CNT end to a first variable voltage source and having a relatively sharp CNT tip at a second end of the at least one CNT in the first array is located at a distance in a range of about 10–200 µm from a substantially constant voltage plate, where the chamber is arranged to receive a gas, having at least one unknown component and having a pressure in a range of about 10⁻²⁻760 Torr, in a region between the at least one CNT and the substantially constant voltage plate;
- a voltage pulse source, to provide voltages, \( V(t_1; 1) \rightarrow V(0) \), at a sequence of times \( t = t_1, (n = 1, \ldots, N1; N1 \geq 3) \) to the at least one CNT in the first array;

at least one of a current meter and a cumulative electrical charge meter (collectively referred to as a “meter”), for measuring at least one of a first associated electrical current \( I(t_1; 1) \), and a first associated cumulative electrical charge \( e(t_1; 1) \) that passes between the at least one CNT in the first array and the substantially constant voltage plate, for each of the \( N1 \) distinct voltages \( V(t_1; 1), V(t_2; 1), \ldots, V(t_N1; 1) \); and

- a computer that is programmed:

(i) to estimate a first measured pulse discharge breakdown threshold voltage \( V(\text{meas}; \text{thr}) \) from a comparison of at least one of (i) three electrical current values \( I(t_{n1}; 1), I(t_{n1}; 1), \) and \( I(t_{n1+m1}; 1) \) with each other, and (ii) three cumulative electrical charge values \( e(t_{n1}; 1), e(t_{n1}; 1), \) and \( e(t_{n1+m1}; 1) \) with each other, for selected numbers \( m1 \geq 1 \) and \( m2 \geq 1 \);

(ii) to provide a threshold discharge voltage value \( V(k; \text{thr}) \) for each of \( K \) candidate gas components, numbered \( k = 1, \ldots, K \) (\( K \geq 1 \));

(iii) to compute an error \( \epsilon(k) \) (\( k = 1, \ldots, K \)) that depends upon a difference between the measured breakdown threshold voltage \( V(\text{meas}; \text{thr}) \) and the threshold discharge voltage value \( V(k; \text{thr}) \);

(iv) when the error \( \epsilon(k) \), for \( k = 1, \ldots, K \), satisfies at least one of the conditions (1) \( \epsilon(k) \geq \epsilon(k; \text{thr}) \), \( (k) \) is a selected error threshold value, and (2) \( \epsilon(k) \)

\[ \leq \min_{1 \leq a \leq K} \epsilon(k) \], to interpret this satisfaction as indicating that the gas component no. \( k = k1 \) is likely to be present in the gas G; and

(v) when no candidate gas component, no. \( k = k1 \), exists that satisfies at least one of the conditions (1) \( \epsilon(k) \geq \epsilon(k; \text{thr}) \) and (2) \( \epsilon(k; \text{thr}) \), to interpret this satisfaction as indicating that none of the gas components no. \( k = 1, \ldots, K \) is likely to be present in the gas G.

10. The system of claim 9, wherein said computer is further programmed so that:

when said error \( \epsilon(k) \), for \( k = 1 \), satisfies both of said conditions (1) \( \epsilon(k) \geq \epsilon(k; \text{thr}) \) and (2) \( \epsilon(k) \leq \min_{1 \leq a \leq K} \epsilon(k) \), to interpret this satisfaction as indicating that said gas component no. \( k = k1 \) is present in said gas G.

11. The system of claim 9, wherein said error \( \epsilon(k) \) is chosen to be \( \epsilon(k) = A \cdot V(\text{meas}; \text{thr}) - V(k; \text{thr}) \), where \( A \) is a selected positive value.

12. The system of claim 9, wherein said computer is further programmed to estimate a first pulse discharge breakdown threshold voltage \( V(1; \text{thr}) \) from a comparison of at least one of (i) three electrical current values \( I(t_{n1}; 1), I(t_{n1}; 1), \) and \( I(t_{n1+m1}; 1) \) with each other, and (ii) three cumulative electrical charge values \( e(t_{n1}; 1), e(t_{n1}; 1), \) and \( e(t_{n1+m1}; 1) \) with each other for the first set of \( N1 \) distinct voltages of (i) \( V(t_{n1}; 1) \leq V(t_{n1}; 1) \leq V(t_{n1+m1}; 1) \) and (ii) \( I(t_{n1}; 1) \leq I(t_{n1}; 1) \leq I(t_{n1+m1}; 1) \).

13. The system of claim 12, wherein:

said pulse voltage source provides said sequence \( V(t_{n1}; 1) \) of said voltages as a monotonic sequence satisfying \( V(t_{n1}; 1) \leq V(t_{n1+1}; 1) \leq \ldots \leq V(t_{N1}; 1) \), with \( V(t_{1}; 1) \) less than a breakdown voltage threshold for said gas; and

said computer is further programmed to interpret occurrence of the simultaneous conditions (i) \( I(t_{n1}; 1) \leq I(1; \text{thr}) \), where \( I(1; \text{thr}) \) is a selected threshold current value, and (ii) \( I(t_{n1+1}; 1) \leq I(1; \text{thr}) \) and (iii) \( V(t_{n1+1}; 1) < V(t_{n1}; 1) \) as indicating that a component in said gas is present having a pulse discharge breakdown threshold voltage \( V(1; \text{thr}) \) satisfying \( V(t_{n1}; 1) \leq V(t_{n1+1}; 1) \).

14. The system of claim 9, wherein:

said pulse voltage source provides said sequence \( V(t_{n1}; 1) \) of said voltages as a monotonic sequence satisfying \( V(t_{n1}; 1) > V(t_{n1+1}; 1) \), with \( V(t_{1}; 1) \) greater than a breakdown voltage threshold for said gas; and

said computer is further programmed to interpret occurrence of the simultaneous conditions (i) \( I(t_{n1}; 1) > I(1; \text{thr}) \), where \( I(1; \text{thr}) \) is a selected threshold current value, and (ii) \( I(t_{n1+1}; 1) \geq I(1; \text{thr}) \) and (iii) \( V(t_{n1}; 1) > V(t_{n1+1}; 1) \) as indicating that a component in said gas is present having a pulse discharge breakdown threshold voltage \( V(1; \text{thr}) \) satisfying \( V(t_{n1+1}; 1) > V(t_{n1}; 1) \).

15. The system of claim 9, wherein:

said pulse voltage source provides said sequence \( V(t_{n1}; 1) \) of said voltages as a monotonic sequence satisfying \( V(t_{n1}; 1) > V(t_{n1+1}; 1) \), with \( V(t_{1}; 1) \) greater than a breakdown voltage threshold for said gas; and

said computer is further programmed to interpret occurrence of the simultaneous conditions (i) \( I(t_{n1}; 1) > I(1; \text{thr}) \), where \( I(1; \text{thr}) \) is a selected threshold current value, and (ii) \( I(t_{n1+1}; 1) \geq I(1; \text{thr}) \) and (iii) \( V(t_{n1+1}; 1) > V(t_{n1}; 1) \) as indicating that a component in said gas is present having a pulse discharge breakdown threshold voltage \( V(1; \text{thr}) \) satisfying \( V(t_{n1}; 1) > V(t_{n1+1}; 1) \).

16. The system of claim 9, wherein:

said pulse voltage source provides said sequence \( V(t_{n1}; 1) \) of said voltages as a monotonic sequence satisfying \( V(t_{n1}; 1) > V(t_{n1+1}; 1) \), with \( V(t_{1}; 1) \) greater than a breakdown voltage threshold for said gas; and

said computer is further programmed to interpret occurrence of the simultaneous conditions (i) \( I(t_{n1}; 1) > I(1; \text{thr}) \), where \( I(1; \text{thr}) \) is a selected threshold current value, and (ii) \( I(t_{n1+1}; 1) \geq I(1; \text{thr}) \) and (iii) \( V(t_{n1+1}; 1) > V(t_{n1}; 1) \) as indicating that a component in said gas is present having a pulse discharge breakdown threshold voltage \( V(1; \text{thr}) \) satisfying \( V(t_{n1}; 1) > V(t_{n1+1}; 1) \).
value, and (ii) \(e(t_{n_1+1}) \geq e(1; \text{thr})\) and (iii) \(V(t_{n_1}; 1) < V(t_{n_1+1}; 1)\) as indicating that a component in said gas is present having a breakdown voltage \(V(1; \text{thr})\) satisfying \(V(t_{n_1}) < V(1; \text{thr}) \leq V(t_{n_1+1}; 1)\).

17. The system of claim 9, wherein:

said voltage pulse source further provides a second spaced apart array of CNTs in said chamber, each CNT in the second array being attached at a first end to said variable voltage source and having a relatively sharp CNT tip at a second end that is directed toward said constant voltage plate, where the second end of at least one CNT in the second array is located at a distance in a range of about 10-200 \(\mu\)m from said plate, to provide a second pulse voltage that is independent of said first pulse voltage provided by said variable voltage source, and where the second array is spaced apart from the first array by a distance of at least 50 \(\mu\)m; and

said voltage pulse source applies second voltage pulses, having known voltages, \(V'(t_{n_2}) = V_0\), at a sequence of times \(t = t_{n_2}, t_{n_2+1}, \ldots, t_{n_2+N_2}\) to the at least one CNT in the second array;

said meter measures at least one of a second associated electrical current \(I'(t_{n_2}; 2)\) and a second cumulative electrical charge \(e'(t_{n_2}; 2)\) that passes between the at least one CNT in the second array and said substantially constant voltage plate, for each of at least \(N_2\) voltages \(\{V'(t_{n_2}; 2)\}\); and

said computer is further programmed to estimate a second pulse discharge breakdown threshold voltage \(V(2; \text{thr})\) from a comparison of at least one of (i) three current values \(I'(t_{n_2-m_3}; 2), I'(t_{n_2}; 2)\) and \(I'(t_{n_2+m_3}; 2)\) with each other, and (ii) three cumulative electrical charge values \(e'(t_{n_2-m_3}; 2), e'(t_{n_2}; 2)\) and \(e'(t_{n_2+m_3}; 2)\) with each other, where \(m_3 \geq 1\) and \(m_4 \geq 1\).