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Jordan

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(54) **MULTI-ELEMENT ELECTRON-TRANSFER OPTICAL DETECTOR SYSTEM**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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Related U.S. Application Data

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(51) **Int. Cl.**[7] **H01L 31/00**

(52) **U.S. Cl.** **250/214.1**; 313/310

(58) **Field of Search** .... 250/214 VT, 330, 250/338.1; 313/103 CM, 310, 523–544

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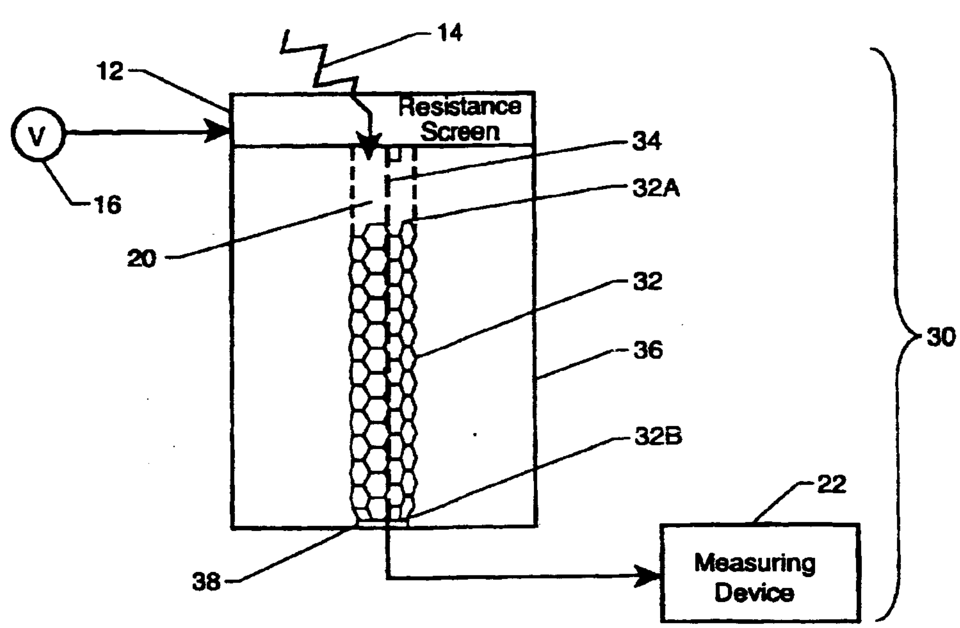
(57) **ABSTRACT**

A multi-element optical detector system includes an electrically resistive screen that is substantially transparent to radiation energy having a wavelength of interest. A plurality of electron transfer elements (e.g., a low work function photoactive material or a carbon nanotube (CNT)-based element) are provided with each having a first end and a second end. The first end of each element is spaced apart from the screen by an evacuated gap. When the radiation energy passes through the screen with a bias voltage applied thereto, transfer of electrons through each element is induced from the first end to the second end such that a quantity indicative of the electrons transferred through each element can be detected.

40 Claims, 6 Drawing Sheets



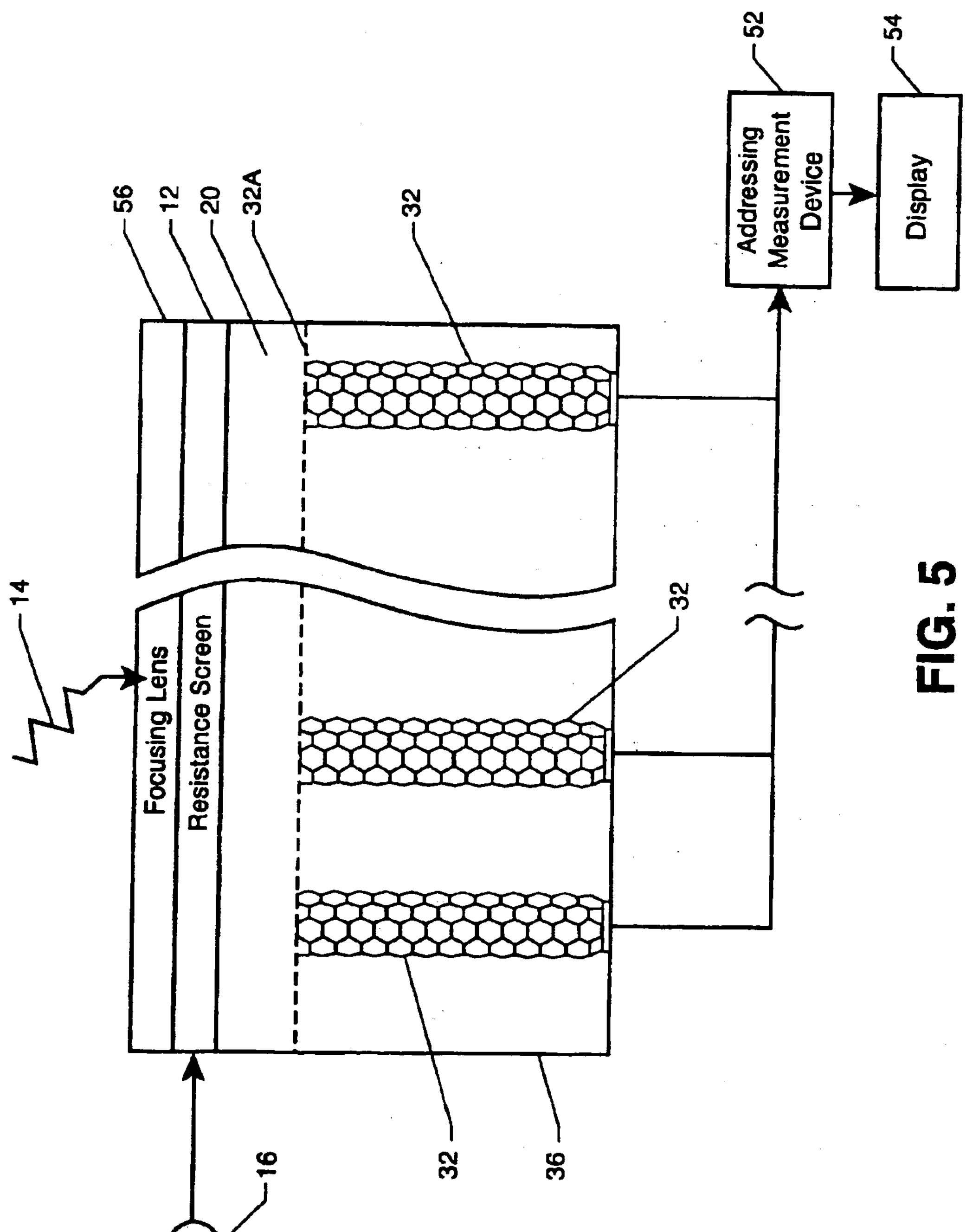

14
Focusing Lens
Resistance Screen
56
12
20
32A
32
32
32
36
16
V
52
Addressing Measurement Device
54
Display

FIG. 5

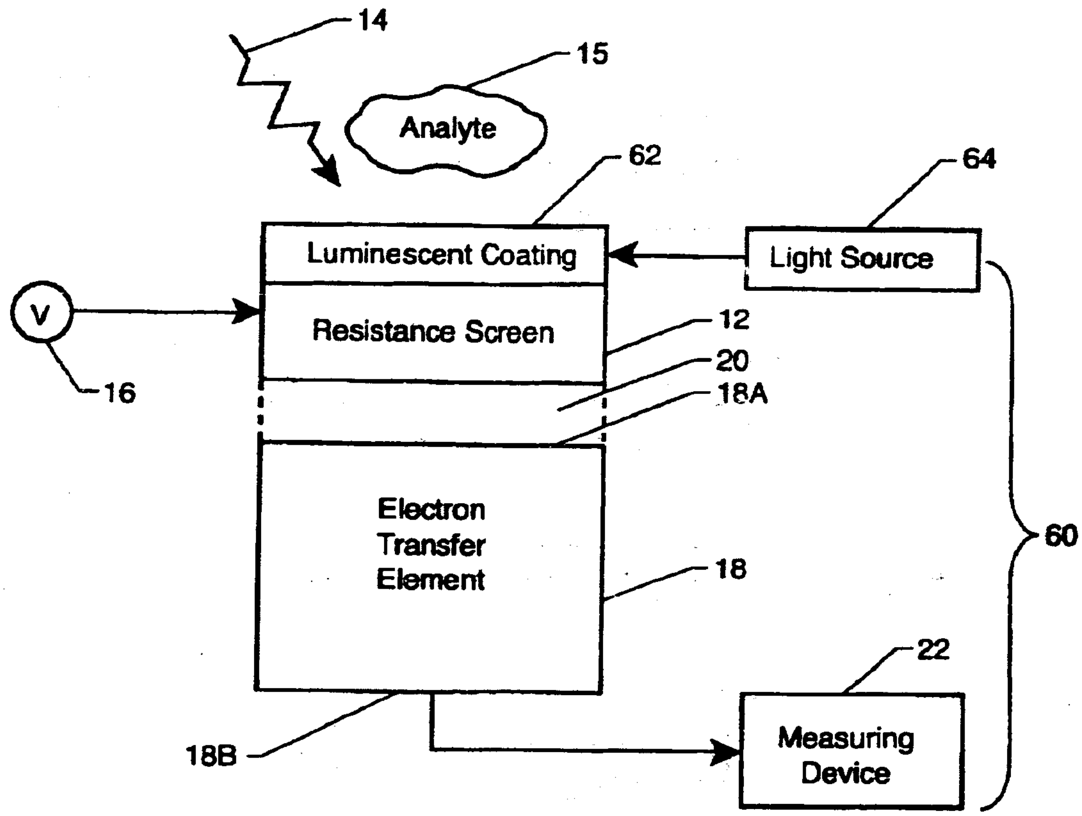

14
15
Analyte
62
64
Luminescent Coating
Light Source
V
Resistance Screen
12
20
16
18A
Electron
Transfer
Element
60
18
22
18B
Measuring
Device

FIG. 6

MULTI-ELEMENT ELECTRON-TRANSFER OPTICAL DETECTOR SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of provisional application 60/276,568 filed on Mar. 14, 2001.

This patent application is co-pending with one related patent application entitled "SINGLE-ELEMENT ELECTRON-TRANSFER OPTICAL DETECTOR SYSTEM" (Ser. No. 10/097,702), by the same inventor as this patent application.

ORIGIN OF THE INVENTION

The invention described herein was made by an employee of the United States Government and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to optical detectors. More specifically, the invention is a multi-element optical detector system for imaging and/or sensing applications that detects and/or measures photo-induced electron transfer through micro-scale electron conduction elements (e.g., carbon nanotubes (CNT), photoactive materials having low work functions, or combinations of these two) that are spaced from a bias voltage screen through which radiation of interest passes.

SUMMARY OF THE INVENTION

In accordance with the present invention, an optical detector system includes an electrically resistive screen that is substantially transparent to radiation energy having a wavelength of interest. A voltage source is provided to apply a bias voltage to the screen. A plurality of electron transfer elements (e.g., a low work function photoactive material, a carbon nanotube (CNT), or a CNT topped with a low work function photoactive material) are provided with each having a first end and a second end. The first end of each element is spaced apart from the screen by an evacuated gap. When the radiation energy passes through the screen with the bias voltage being applied thereto, transfer of electrons through each element is induced from the first end to the second end thereof. A detector, electrically coupled to the second end of each individual element, detects a quantity indicative of the electrons transferred through each element. The optical detector system can operate as described for imaging applications and can be adapted for sensing applications by providing one or more types of analyte-sensitive, luminescent coatings on the screen.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic view of a single-element optical detector system constructed in accordance with the present invention;

FIG. 2 is a schematic view of one embodiment of a single-element optical detector system having a carbon nanotube (CNT) electron transfer element;

FIG. 3 is a schematic view of another embodiment of a single-element optical detector system having its electron transfer element constructed from a CNT topped with a low-work function photoactive material;

FIG. 4 is a schematic plan view of an embodiment of a multi-element imaging system constructed from single-element optical detector systems;

FIG. 5 is a schematic view of the multi-element imaging system using a common resistance screen and a focusing lens;

FIG. 6 is a schematic plan view of a single-element optical detector system capable of sensing an analyte of interest;

FIG. 7 is a schematic plan view of an embodiment of a multi-element sensing system constructed from single-element optical detector systems;

FIG. 8 is a schematic plan view of a multi-element system that combines imaging and sensing capabilities; and

FIG. 9 is a schematic side view of the combined imaging and sensing multi-element system.

DETAILED DESCRIPTION OF THE INVENTION

Referring now to the drawings, and more particularly to FIG. 1, a single-element optical detector system in accordance with an embodiment of the present invention is shown and referenced generally by numeral **10**. Optical detector system **10** forms the basic structure used to construct novel imaging elements/systems, sensing elements/systems, or combined imaging and sensing systems, each of which will be described further below.

Optical detector system **10** has a resistance screen **12** disposed in the path of radiation energy **14** that is to be detected and, if desired, measured. Radiation energy **14** can be any visible or invisible light energy. Resistance screen **12** is any electrically resistive material (e.g., electrical resistivity of approximately 60 ohms per square or greater) that is fully transparent or at least substantially transparent to the wavelength range of radiation energy **14**. Electrically coupled to resistance screen **12** is a voltage source **16** that applies a biasing voltage to resistance screen **12**. Spaced apart from resistance screen **12** is an electron transfer element **18** that can transfer electrons therethrough after it is exposed to radiation energy **14**. As will be explained further below, element **18** is preferably a carbon nanotube (CNT) based element, but could also be any photoactive material capable of photo-induced electron transfer at the micro-scale level. A small gap **20** (i.e., on the order of 100 microns or less) is defined between resistance screen **12** and one end **18A** of electron transfer element **18**. For reasons that will be explained further below, gap **20** is preferably evacuated. The opposing end **18B** of electron transfer element **18** is electrically coupled to a measuring device **22** which can be an ammeter that measures current, a voltmeter that measures voltage, an electron counter that counts electrons reaching end **18B**, or a device that measures any combination of current, voltage and electron counts.

In operation, a bias voltage is applied to resistance screen **12** while it is exposed to incident radiation energy **14**. Radiation energy **14** passes through resistance screen **12** and is incident on electron transfer element **18** at end **18A** thereof. The impingement of radiation energy **14** on electron transfer element **18** induces photoelectron transport therethrough, i.e., electron loss in element **18**. The resulting electron vacancies or "holes" left in element **18** are filled with electrons sourced from the voltage biased resistance screen **12** resulting in a current flow. The photo-induced electron transfer through element **18** is measured at its end **18B**. Evacuation of gap **20** minimizes electron collisions in gap **20** thereby ensuring that the vast majority of electrons released from screen 12 will be transferred to element 18. The electron transfer is then detected/measured at end 18B by measuring device 22.

As noted above, optical detector system 10 forms the basic structure for an optical imaging element and system made from an array of such elements. At the heart of each basic structure is electron transfer element 18 which, in general, can be any photoactive material that exhibits electron release/flow following optical interrogation by light of the desired wavelength. The energy required to effect electron release is given by the band-gap energy for a material, and is typically expressed in units of energy, e.g., electron volts. This measurement can be converted to wavelength to provide a measure of the longest wavelength (i.e., lowest energy) photon that will induce the photoelectric effect. Thus, electron transfer element 18 can be used to tailor the sensitivity of optical detector system 10 to specific wavelengths of interest. For example, a photoactive material that does not require a large amount of energy (or "work function") to induce the release of electrons therefrom can be used to construct an optical detector system that is sensitive to very short wavelengths. The work function is the amount of energy required for an electron to be released and depends on the number of electron shells an atom has. That is, the greater the number of shells, the less the work function. This is due to what is known as the "weak force" which is the force that the nucleus of an atom has to retain its electrons. The weak force decreases as the distance from the electron to the atom's nucleus increases. As an electron's weak force decreases, so does the energy needed to free it from the atom.

Photoactive materials having low work functions include, for example, cesiated metals such as cesiated silver oxide (AgOCs), cesiated sodium potassium antimony ([Cs] Na2KSb), and cesiated antimony (SbCs). Other low work function materials include certain semi-conductor materials such as indium gallium arsenic phosphide (InGaAsP), gallium arsenide (GaAs) and sodium potassium antimony (Na2KSb). Note that each of the above-described materials has a preferable wavelength or bandwidth at which electron transfer therethrough is optimized.

To construct optical detector systems in accordance with the present invention that have a high-degree of spatial resolution, sensitivity and bandwidth, it is preferred that electron transfer element 18 be constructed partially or totally from a carbon nanotube (CNT). As is known in the art, CNTs are longitudinally extending carbon fibril structures having a high electrical conductivity. A variety of known growth techniques can be used to construct single-wall (SW) and multi-wall (MW) CNTs having diameters as small as one nanometer. Accordingly, FIG. 2 illustrates a single imaging element 30 using a CNT. Common reference numerals will be used for elements already described above.

In single imaging element 30, resistance screen 12 (biased by a biasing voltage from source 16) is exposed to radiation energy 14. Resistance screen 12 can be realized by a substantially transparent wire mesh screen. However, if absolute transparency over a broad wavelength spectrum is desired, resistance screen 12 can be realized by a sheet of indium tin oxide. Spaced apart from resistance screen 12 by gap 20 is a CNT 32 positioned such that its longitudinal axis 34 is substantially perpendicular to resistance screen 12. Note that system 30 will still function if longitudinal axis 34 is not perpendicular to resistance screen 12, although some electron transfer losses may occur. CNT 32 is representative of a single-wall CNT (SWCNT) or a multi-wall (MWCNT). Although current fabrication techniques favor MWCNTs over SWCNTs (owing to the complexities associated with controlling alignment of SWCNTs during the growth thereof), it is to be understood that the present invention can use either type.

The gap 20 between resistance screen 12 and one longitudinal end 32A of CNT 32 is on the order of 100 microns or less. To provide for evacuation of gap 20, an evacuated chamber 36 can be provided to enclose resistance screen 12 and CNT 32 with screen 12 still being capable of having radiation energy 14 impinge thereon. A metal electrode 38 can be coupled to the other longitudinal end 32B of CNT 32 to provide a measurement point for measuring device 22.

If it is desired to be sensitive to a particular wavelength band of radiation energy 14, the optical detector system can be constructed as illustrated in FIG. 3. More specifically, optical detector system 40 is identical to system 30 except that end 32A of CNT 32 is "topped" with a layer of a low work function photoactive material (PA) 42, several of which were described above. In this way, electron transfer through CNT 32 is induced only by the presence of a radiation energy 14 that is in the wavelength region to which photoactive material 42 is sensitive.

Each of the above-described optical detector system "elements" can be used in an imaging system constructed from an array of such elements. This embodiment is illustrated schematically in FIG. 4 where an array 50 of optical detector elements based on system 10 are provided. In this plan view, the resistance sheet is omitted for clarity of illustration so that each of electron transfer elements 18 is visible. Note that systems 30 or 40 could also be used to construct array 50. Further, a combination of systems 10, 30 and 40 could be used to construct such an imaging array. In this way, portions of the imaging array could be made more sensitive to a particular wavelength region of incoming radiation energy. Also, note that an image pixel can be formed by one or more of electron transfer elements 18.

Each element 18 is uniquely addressable and can have its electron transfer amounts detected/measured by addressing measurement device 52. That is, measurement device 52 functions as an individual measuring device (analogous to measurement device 22 described above) for all of elements 18. The simultaneously-read outputs from device 52 can be provided to a display 54.

Although each element in an imaging array can be constructed individually, some economy of scale can be applied in the construction process without departing from the scope of the present invention. For example, as illustrated in FIG. 5, a single resistance screen 12 can be used to span gap 20 between ends 32A of an array of CNTs 32 that reside in a common evacuated chamber 36. Further, if necessary, a focusing lens 56 can be placed in front of resistance screen 12 to bring an imaged area/object into focus.

The present invention can also be used in a sensing capacity. To illustrate this, optical detector system 10 (FIG. 1) has been modified to yield optical detector system 60 shown in FIG. 6 that can sense an analyte of interest. However, it is to be understood that either of optical detector systems 30 and 40 could be similarly modified without departing from the scope of the present invention. As used herein, "analyte" means any gas or liquid-phase species for which an optical transduction mechanism exists or could be developed.

Optical detector system 60 includes a luminescent coating layer 62 deposited on resistance screen 12. Layer 62 is representative of an optical transduction mechanism and is generally realized by any coating that experiences changes

32. An optical detector system as in claim 25 wherein said detection means comprises means for counting the number of electrons reaching said second end of each of said plurality of MWCNTs.

33. An optical detector system, comprising:

resistance means transparent to radiation energy having a wavelength of interest and being electrically resistive;

a voltage source for applying a bias voltage to said resistance means;

a plurality of single-wall carbon nanotubes (SWCNTs), each of which has a longitudinal axis extending between a first end and a second end thereof, each of said plurality of SWCNTs positioned with the longitudinal axis approximately perpendicular to said resistance means, said first end of each of said plurality of SWCNTs being spaced apart from said resistance means by a gap;

evacuation means cooperating with said gap for placing said gap in an evacuated state wherein, when radiation energy passes through said resistance means with the bias voltage being applied thereto, transfer of electrons through each of said plurality of SWCNTs is induced from said first end to said second end thereof; and

detection means, electrically coupled to said second end of each individual one of said plurality of SWCNTs, for detecting a quantity indicative of the electrons transferred through said each of said plurality of SWCNTs.

34. An optical detector system as in claim 33 further comprising a luminescent-based, analyte-sensing means positioned to have radiation energy pass therethrough before impingement on at least a portion of said resistance means, said analyte-sensing means changing in terms of at least one luminescent property in the presence of an analyte of interest.

35. An optical detector system as in claim 33 wherein said resistance means is a material having an electrical resistivity of at least approximately 60 ohms per square.

36. An optical detector system as in claim 33 wherein said resistance means is indium tin oxide.

37. An optical detector system as in claim 33 further comprising a photoactive material positioned on said first end of at least one of said SWCNTs.

38. An optical detector system as in claim 33 wherein said detection means comprises an ammeter.

39. An optical detector system as in claim 33 wherein said detection means comprises a voltmeter.

40. An optical detector system as in claim 33 wherein said detection means comprises means for counting the number of electrons reaching said second end of each of said plurality of SWCNTs.

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