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(54) Title: ZINC OXIDE SULFUR SENSOR

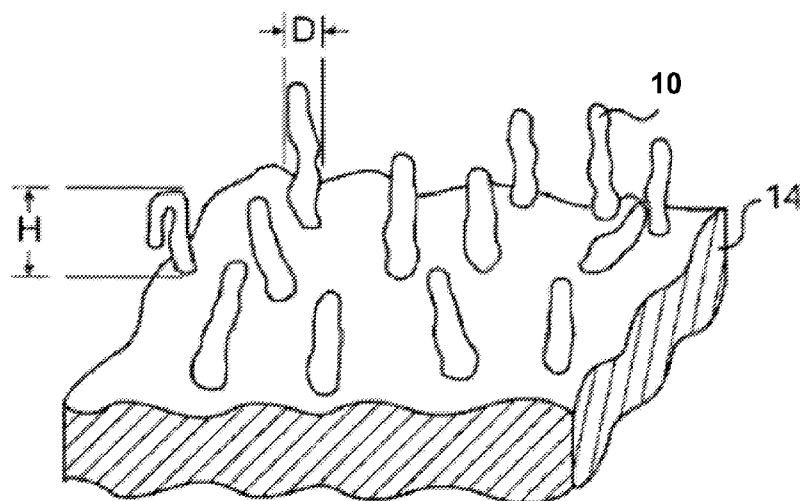


Fig. 1

(57) Abstract: Sulfur sensors are formed by coating a conductive substrate with ZnO microstructures that are reactive with sulfur in liquids, such as fuel, using MOCVD. The ZnO is changed to ZnS over time and causes the voltage across the sensors to change under a constant current by at least about 25%. The time required for such saturation to occur can then be correlated to a sulfur concentration in the liquid.

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Description

ZINC OXIDE SULFUR SENSOR

Technical Field

The present invention relates generally to sulfur sensors. More particularly, the present invention relates to sulfur sensors that can be used to detect ultra low concentrations of sulfur in liquids, such as below even 15 ppm.

Background

It is important to be able to accurately and reliably measure the concentration of sulfur in liquids, as various chemical reactions may take place that would release sulfur compounds into the atmosphere or onto physical structures around the sulfur-containing liquid. For example, the combustion of diesel fuel typically generates sulfur oxides (SO_2 , SO_3) and sulfuric acid (condensate H_2SO_4), both of which are components of acid rain. Further, these sulfur compounds have been linked to catalyst poisoning in diesel particulate filters (DPFs) and sulfuric acid condensation and corrosion of engine components, such as the cooler and piston ring liner components. Such phenomena are found when using both high sulfur (>350 ppm) and low sulfur (10 - 350 ppm) fuels.

For various reasons, including the sensitivity of aftertreatment components to sulfur compounds, many modern diesel engines are now being designed to use Ultra Low Sulfur Diesel fuel (<15 ppm S). Accordingly, the sulfur level of the fuel source is of utmost importance for optimum machine performance. While sulfur detection in liquids at levels below 15 ppm is attainable in a laboratory or other test setting, such detection is not feasible in the field with an accurate, portable, reliable, quick, and inexpensive sensor.

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Examples of known means of detecting sulfur at ultra-low levels include Flame Photometry Detection (FPD) and Inductively Coupled Plasma (ICP) devices, but both are more appropriately used in the laboratory setting because of their size and duration of test cycles. Accordingly, a desire for a fast and inexpensive
5 detection of sulfur level in diesel fuels, or possibly an on-board diagnostic tool for determining the same, persists.

Summary of the Invention

In one aspect, the present disclosure is directed to a sensor for
10 determining a sulfur concentration in a liquid. The sensor comprises a substrate that includes a conductive material. The sensor also includes zinc oxide microstructures protruding from the substrate.

In another aspect, the present disclosure is directed to a sulfur concentration detection system. The detection system comprises a sensor having
15 a substrate including a conductive material and zinc oxide microstructures protruding from the substrate. The system includes a current source and a voltage detector, wherein the current source and voltage detector are connected to the substrate.

In yet another aspect, the present disclosure is directed to a
20 method for determining the sulfur concentration in a liquid. The method comprises exposing the liquid to a sulfur sensor, where the sensor has a substrate including a conductive material and zinc oxide microstructures protruding from the substrate. The method then includes applying a constant current to the substrate, monitoring the voltage corresponding to the applied current, and
25 measuring the amount of time required for the voltage to change by at least about 25%. After this, the method includes the step of correlating the time required for the voltage to change by at least about 25% to a concentration of sulfur in the liquid.

Brief Description of the Drawings

Figure 1 is a cross-sectional illustration of zinc oxide microstructures on a conductive substrate as disclosed herein.

Figure 2 is an SEM micrograph of the surface of a substrate coated with zinc oxide microstructures at approximately 5000x.

Figure 3 is a chart showing the change in voltage over time for differing concentrations of sulfur in liquid using a sensor disclosed herein.

Figure 4A is a photomicrograph of the surface of a substrate coated with ZnO microstructures as disclosed herein at about two hours of growth at about 1900x.

Figure 4B is a photomicrograph of the surface of a substrate coated with ZnO microstructures as disclosed herein at about 3.5 hours of growth at about 1900x.

Whenever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts.

Detailed Description

With reference to the drawings, Figure 1 shows a cross-section of a zinc oxide (ZnO) sulfur sensor according to the disclosure. The sulfur sensor has ZnO microstructures 10 protruding from a substrate 14. While the term “microstructures” is used herein to describe the nature and size of the protrusions, one skilled in the art should understand that the actual scale of said protrusions may approach or enter the nano-scale or, alternatively, be larger than the micro-scale.

The sulfur sensor is designed based on the physical adsorption of organ-sulfur compounds onto ZnO. The rate of physical adsorption of organ-sulfur compounds onto ZnO is a function of surface area, which can be increased by controlling the shape of the protrusions when producing the coating. This physical adsorption is based, as least in part, on the good sorption affinity of ZnO

with organo-sulfur compounds because of the crystal phase in the ZnO coating of microstructures. The physical adsorption of organo-sulfur compounds onto the ZnO protrusions results in a change in resistivity of the outer layer of the ZnO microstructures. The amount of changed material corresponds directly to the
5 amount of sulfur in the liquid available to react with the zinc in ZnO microstructures 10, which can be measured by measuring the voltage change for a known current applied to the sulfur sensor.

Substrate 14 of the sulfur sensor is a conductive material capable of supporting ZnO microstructures and being used to carry a current for
10 determining the voltage change in the microstructures. Exemplary materials include copper or a stainless steel, such as 316 stainless steel.

ZnO microstructures 10 may be formed on substrate 14 using any suitable deposition technique. ZnO microstructures 10 may take on a variety of shapes which are suitable for reaction with the sulfur in the liquid. One
15 advantage to forming microstructures having a protruding orientation away from substrate 14 is the increased surface area available to interact with the sulfur compounds, which not only increases the amount of ZnO available for the physical adsorption, but also increases the sensitivity of the sulfur level measurement. ZnO microstructures 10 may, for example, take on the shape of
20 micro-rods or micro-ribbons. Such forms can be readily achieved using Metal Organic Chemical Vapor Deposition (MOCVD), or any other suitable coating or deposition process known in the art.

As shown in Figure 1, ZnO microstructures 10 protrude outward from conductive substrate 14, designated as the measurement H, by at least about
25 0.1 μm , such as between about 0.1 μm and about 1.0 μm , between about 0.1 μm and about 200 μm , or between about 0.1 μm and about 1.0 μm . Moreover, the width of the micro-ribbon or diameter of the micro-rod, shown as measurement D, is at least about 0.1 μm , such as between about 0.1 μm and about 3 μm , or

between about 0.1 μm and about 1.5 μm , such as between about 0.1 μm and about 1.0 μm .

Figure 2 shows an SEM micrograph of the surface of a ZnO sulfur sensor according to the disclosure. As can be seen in Figure 2, the density of ZnO microstructures 10 is at least about 60% of the surface area of substrate 10. In most instances, however, complete coverage of substrate 10 is not desirable, as such dense coverage may inhibit ZnO interaction with sulfur in the liquid. Accordingly, the coverage of ZnO microstructures 10 on the surface of substrate 10 is between about 30% - 99%. Moreover, it has been discovered that the density of the microstructures may be dependent on the composition of the substrate. For example, when the substrate is copper or another highly conductive substrate, the coverage of ZnO microstructures 10 may be lower, such as between about 30% - 80%, or between about 30% - 60%, or even between about 30%-40%. But for less conductive substrate materials, such as stainless steel, the coverage of ZnO microstructures 10 may be higher, such as between about 60% - 99%, such as between about 75% - 98%, or between about 85% - 98%.

Industrial Applicability

The sensor disclosed herein is particularly useful in field applications to allow operators to determine the sulfur content of a fuel before introducing the fuel into the machine. The sensor disclosed herein may be modified to be a disposable sensor, a reusable sensor, or an on-board sensor that determines the sulfur content of the fuel in the fuel tank neck before an appreciable amount of fuel is introduced.

Figure 3 shows the results of exposing a series of exemplary ZnO sulfur sensors formed according to the disclosure to a variety of liquids having various sulfur concentrations. Specifically, the ZnO microstructures were formed

on copper substrates using MOCVD. The results show how the voltage applied across Sensor A at a constant current changed over time when the sensor was exposed to a liquid having 350 ppm sulfur. Sensor B was exposed to a liquid having 15 ppm sulfur, and Sensor C was exposed to a liquid having 1 ppm sulfur.

5 As can be seen, Sensor A reached a saturation point at about 2 minutes, while Sensor B was saturated at about 5.8 minutes and Sensor C was saturated at about 12.5 minutes.

According to the results of the experiment that yielded the data for Figure 3, an operator could monitor the amount of time necessary for saturation of a ZnO sulfur sensor, as indicated by a change in voltage across the sensor of at

10 least about 25%, or at least about 35%, or even at least about 50%. The operator could then correlate the time necessary for saturation of the sensor to a sulfur content using a lookup table, or the correlation could be automated using known automating techniques, such as a computer accessing a series of lookup tables,

15 and an absolute sulfur reading could be issued to the operator.

To form the ZnO microstructures on the conductive substrate, any suitable deposition and/or growth method known in the art may be used. For example, as noted above, MOCVD may be used to form ZnO deposits on the conductive substrate. Figures 4A and 4B show the affect of the time of the

20 deposition process on the size and density of the ZnO microstructures on the conductive substrate. Figure 4A shows ZnO microstructures that have been grown over about two hours, whereas Figure 4B shows ZnO microstructures grown under the same conditions over about 3.5 hours. The thickness of the ZnO micro-structures shown in Figure 4A is about 0.7 μm and the density is

25 appropriate to allow the ZnO microstructures to grow in highly random directions away from the substrate. By comparison, the thickness of the ZnO microstructures shown in Figure 4B is about 1.0 μm . While this thickness in itself is acceptable, the density of the ZnO on the surface of the conductive substrate is too high, nearing 100%, which inhibits interaction between the

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microstructures and the liquid. Such a high density is indicated in the photomicrograph from the end-on view of nearly all of the microstructures, which suggests that the density is so high, the ZnO microstructures are forced to grow in a highly compact, ordered fashion away from the substrate.

5 While the disclosure has referred to the microstructures as being ZnO microstructures, one skilled in the art should appreciate that the microstructures may have incidental amounts of other elements, likely drawn from the substrate during the deposition and growth process. For example, when the conductive substrate is a stainless steel, the microstructures may have
10 between about 1.0 – 5.0 wt% C, between about 14.0 – 24.0 wt% O, between about 0.5 – 1.5 wt% Cr, and between about 2.5 – 7.0 wt% Fe, the balance being Zn. In one example, analysis showed that ZnO microstructures grown on a stainless steel substrate had the following composition, by weight percent:

15 C - 3.31
 O - 17.90
 Cr - 1.04
 Fe - 4.53
 Zn - 73.22

 Regarding the time necessary to accurately detect the sulfur
20 content in the liquid, among other factors, this is highly dependent on the conductivity of the substrate, the total surface area of the ZnO microstructures exposed to the liquid, and the sulfur concentration of the liquid. In one example where ZnO microstructures were formed on a stainless steel substrate, the following data was collected for the corresponding sulfur concentration:

25

<u>Sample</u>	<u>Sulfur Level (ppm)</u>	<u>Response Time (s)</u>	<u>Potential (V)</u>
1	5	95	4.5
2	386	70	8.0
3	4940	50	15.5

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As can be seen from this data, as sulfur level of the liquid increases, the response time decreases and the voltage increases when a ZnO sulfur sensor formed per this disclosure is used to test the sulfur level of fuel.

Although the present inventions have been described with
5 reference to exemplary embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention. For example, although different exemplary embodiments may have been described as including one or more features providing one or more benefits, it is contemplated that the described features may be interchanged
10 with one another or alternatively be combined with one another in the described exemplary embodiments or in other alternative embodiments. Because the technology of the present invention is relatively complex, not all changes in the technology are foreseeable. The present invention described with reference to the exemplary embodiments and set forth in the following claims is manifestly
15 intended to be as broad as possible. For example, unless specifically otherwise noted, the claims reciting a single particular element also encompass a plurality of such particular elements.

Claims

1. A sensor for determining a sulfur concentration in a liquid,
the sensor comprising:

a substrate comprising a conductive material; and
5 zinc oxide microstructures protruding from the substrate.
2. The sensor of claim 1 wherein the microstructures are rod-
like in form.
3. The sensor of claim 1 wherein the microstructures are
ribbon-like in form.
- 10 4. The sensor of claim 1 wherein the microstructures are at
least about 0.1 μm wide.
5. The sensor of claim 1 wherein the microstructures protrude
15 from the substrate at least about 0.1 μm .
6. The sensor of claim 1 wherein the microstructures protrude
from the substrate between about 0.1 μm and about 1.0 cm.
- 20 7. The sensor of claim 1 wherein the substrate has a width of
at least about 2.0 mm and a length of at least about 2.0 mm.
8. A sulfur concentration detection system, the detection
system comprising:
25 a sensor having a substrate comprising a conductive material and
zinc oxide microstructures protruding from the substrate;
a current source; and

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a voltage detector;
wherein the current source and voltage detector are connected to
the substrate.

9. A method for determining the sulfur concentration in a
5 liquid, the method comprising:
exposing the liquid to a sulfur sensor, the sensor having a substrate
comprising a conductive material and zinc oxide microstructures protruding from
the substrate;
applying a constant current to the substrate;
10 monitoring the voltage corresponding to the applied current;
measuring the amount of time required for the voltage to change
by at least about 25%;
correlating the time required for the voltage to change by at least
about 25% to a concentration of sulfur in the liquid.

15

10. The method of claim 13 wherein the liquid is fuel.

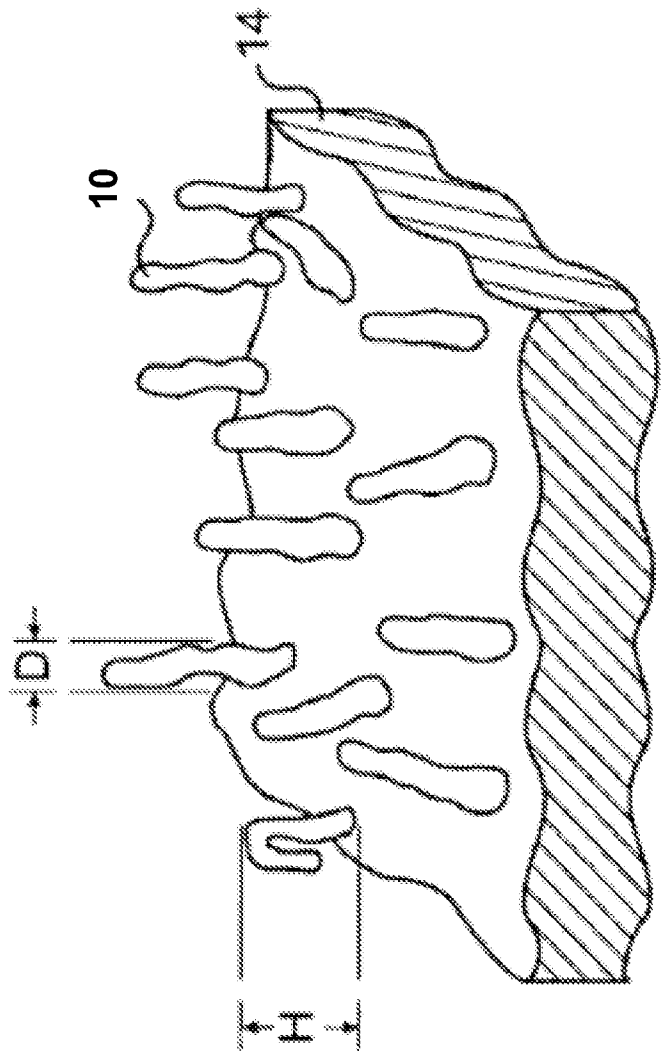


Fig. 1

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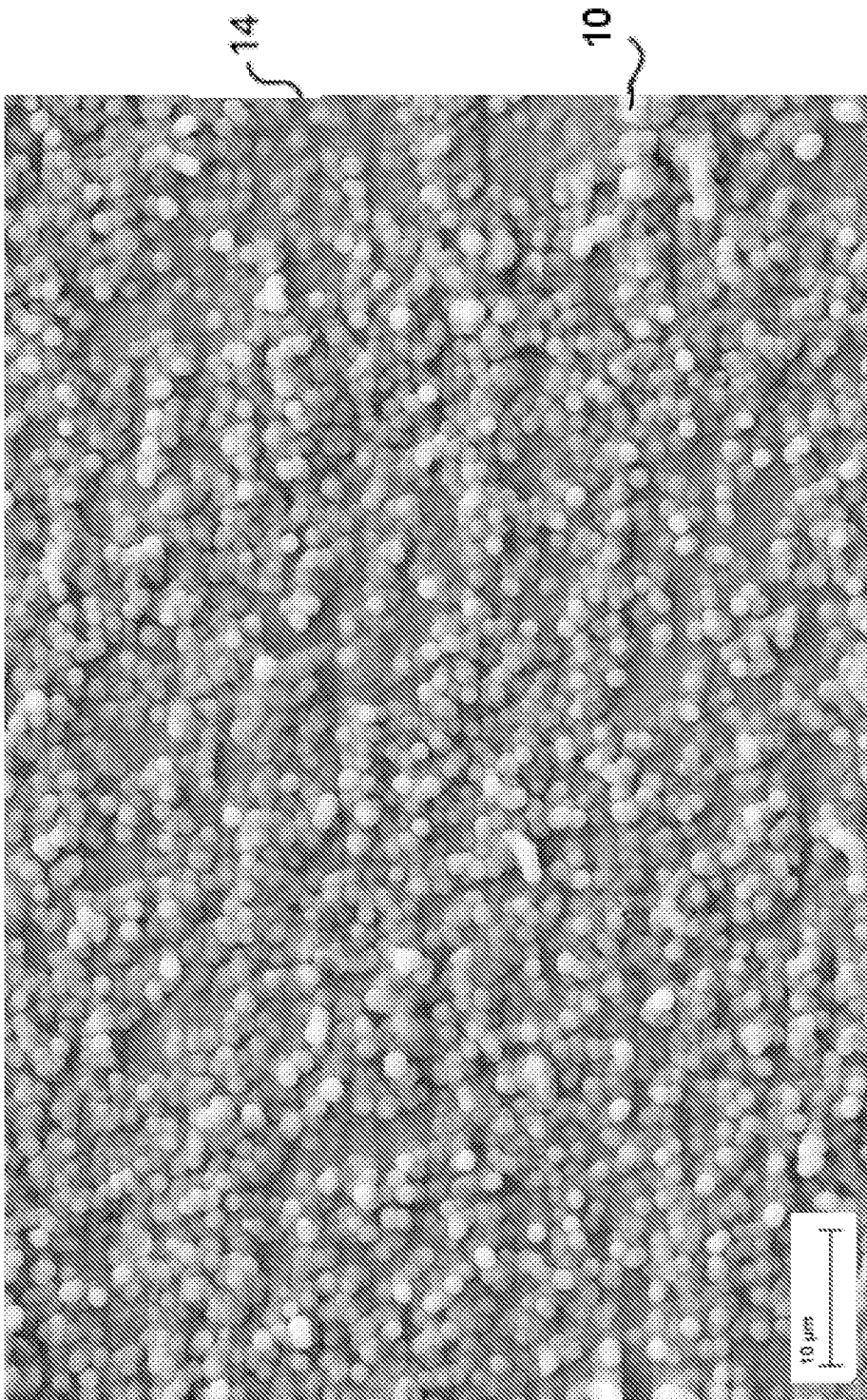


Fig. 2

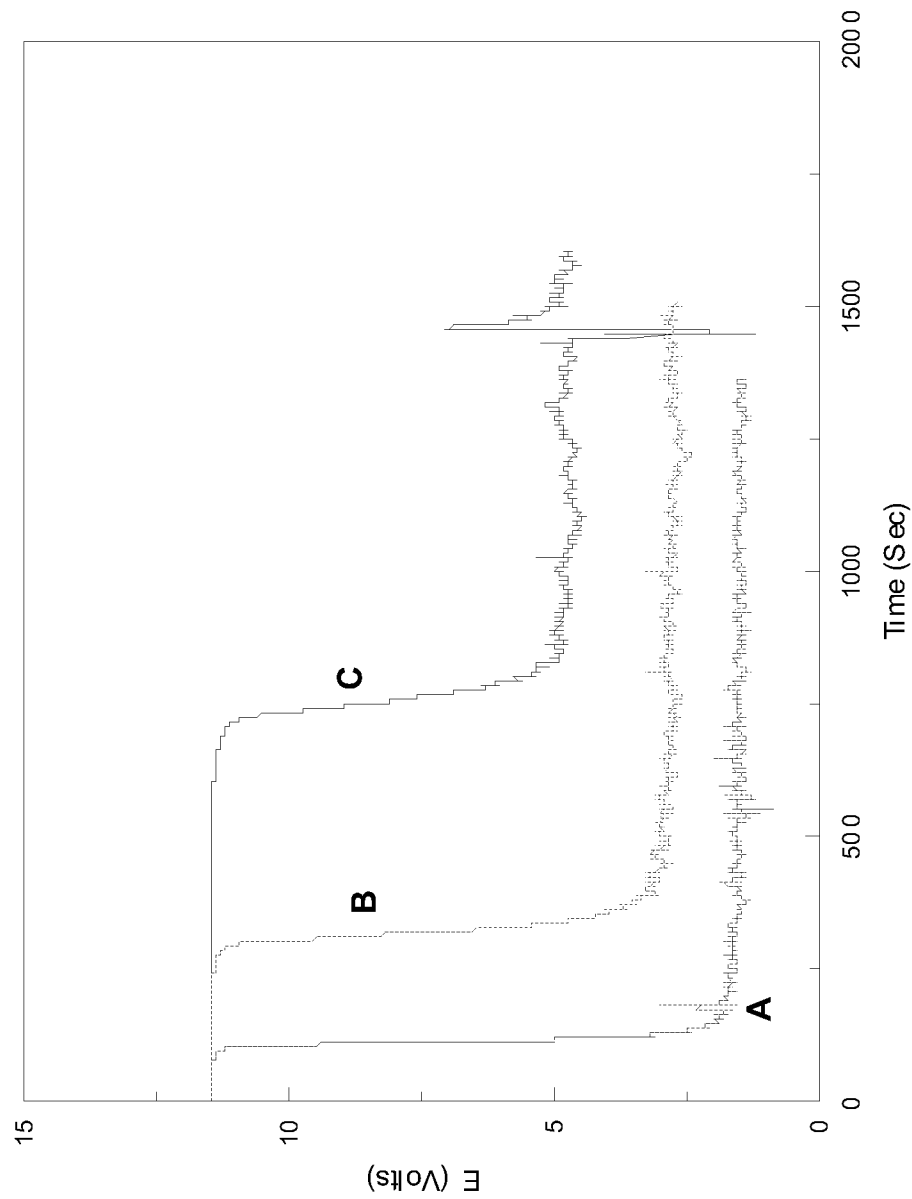


Fig. 3

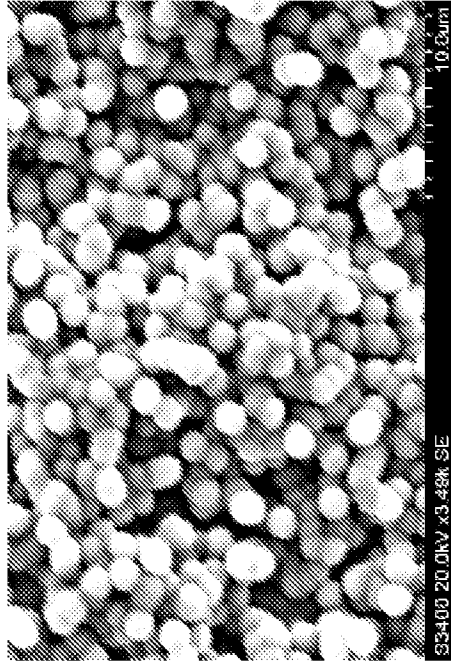


Fig. 4B

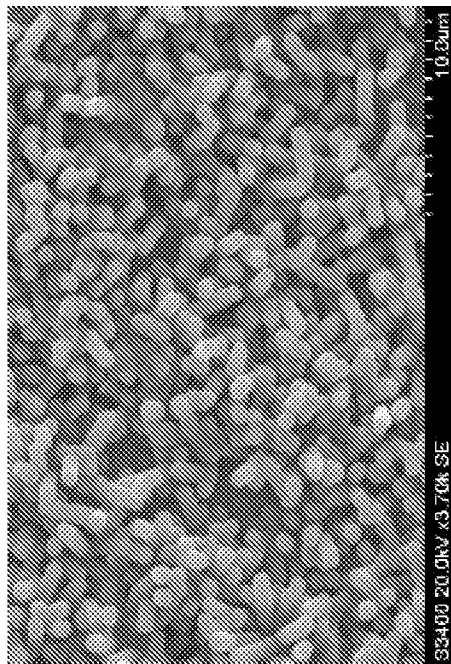


Fig. 4A