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Rahimi

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(54) **SENSOR SYSTEM AND METHOD FOR GAMMA RADIATION DOSE MEASUREMENT**

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G01T 1/02 (2006.01)
H01L 27/30 (2006.01)

(Continued)

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CPC **G01T 1/026** (2013.01); **H10K 39/32** (2023.02); **H10K 77/111** (2023.02)

(58) **Field of Classification Search**
None
See application file for complete search history.

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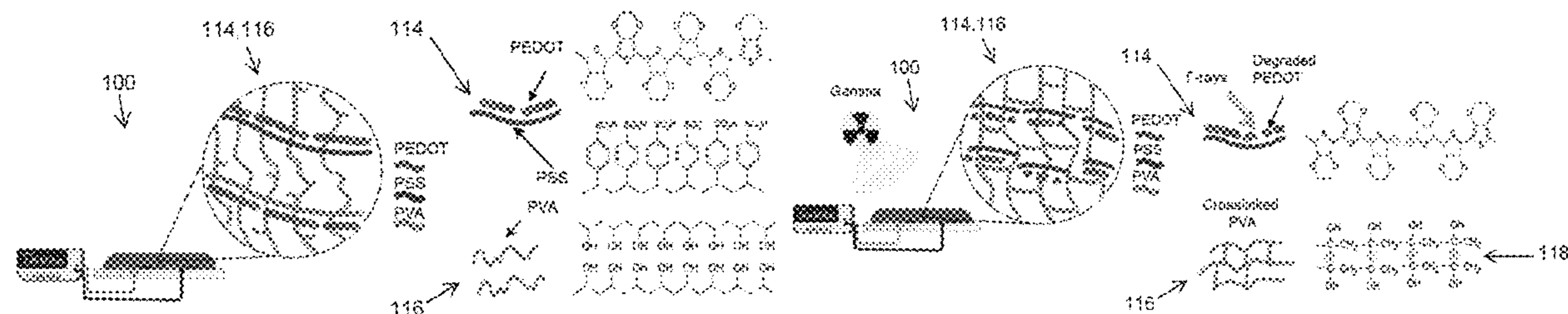
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(57) **ABSTRACT**

A printed radiation sensor that includes a substrate, an interdigitated electrode, and a conductive polymeric film. The interdigitated electrode including a first electrode with a plurality of first electrode digits and a second electrode with a plurality of second electrode digits. The interdigitated electrode disposed on the substrate. The conductive polymeric film including a blend of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) and polyvinyl alcohol (PVA). The PEDOT:PSS is configured to provide an electrically conductive medium. The PVA is configured to provide ductility and stability of the printed radiation sensor. Upon radiation exposure, the PVA is further configured to crosslink within a material matrix of the printed radiation sensor militating against the recombination of chain scission by forming a semi-interpenetrating polymer network (SIPN) with the PEDOT:PSS to provide an enhanced and stable impedance reading.

20 Claims, 12 Drawing Sheets



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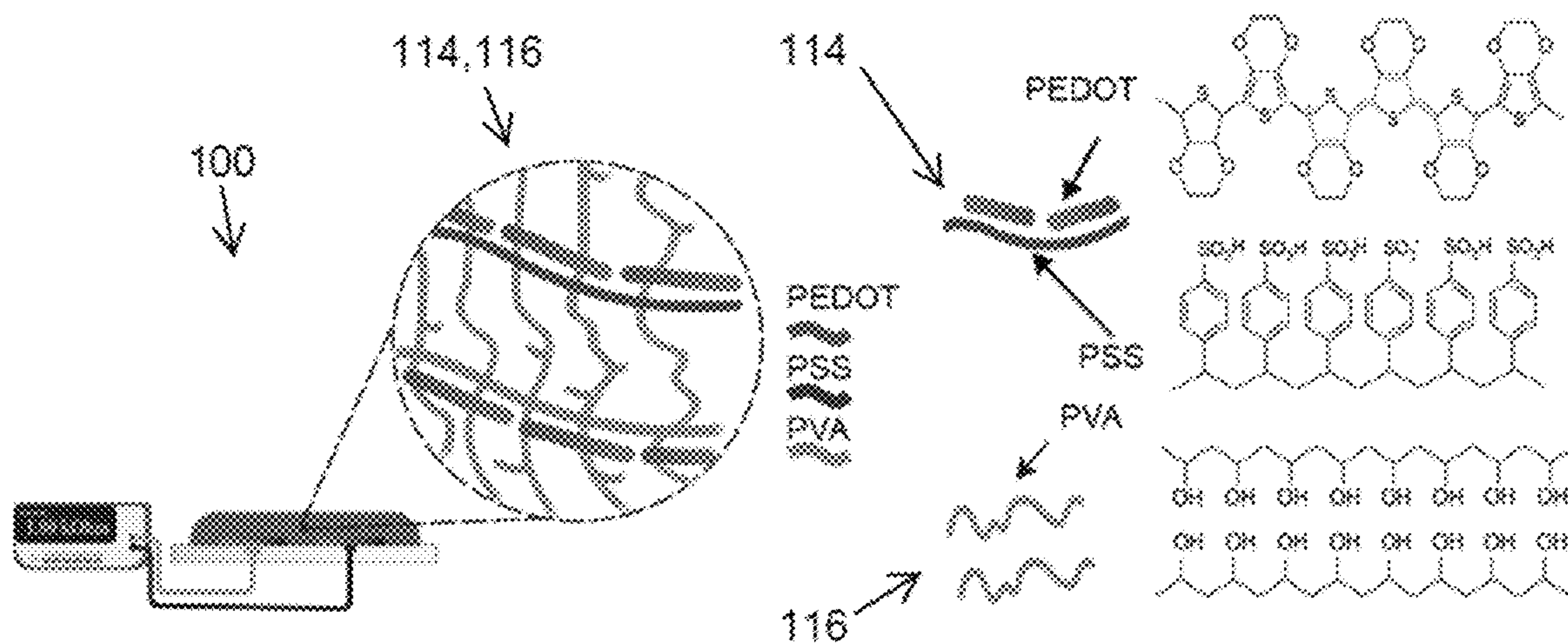


FIG. 1A

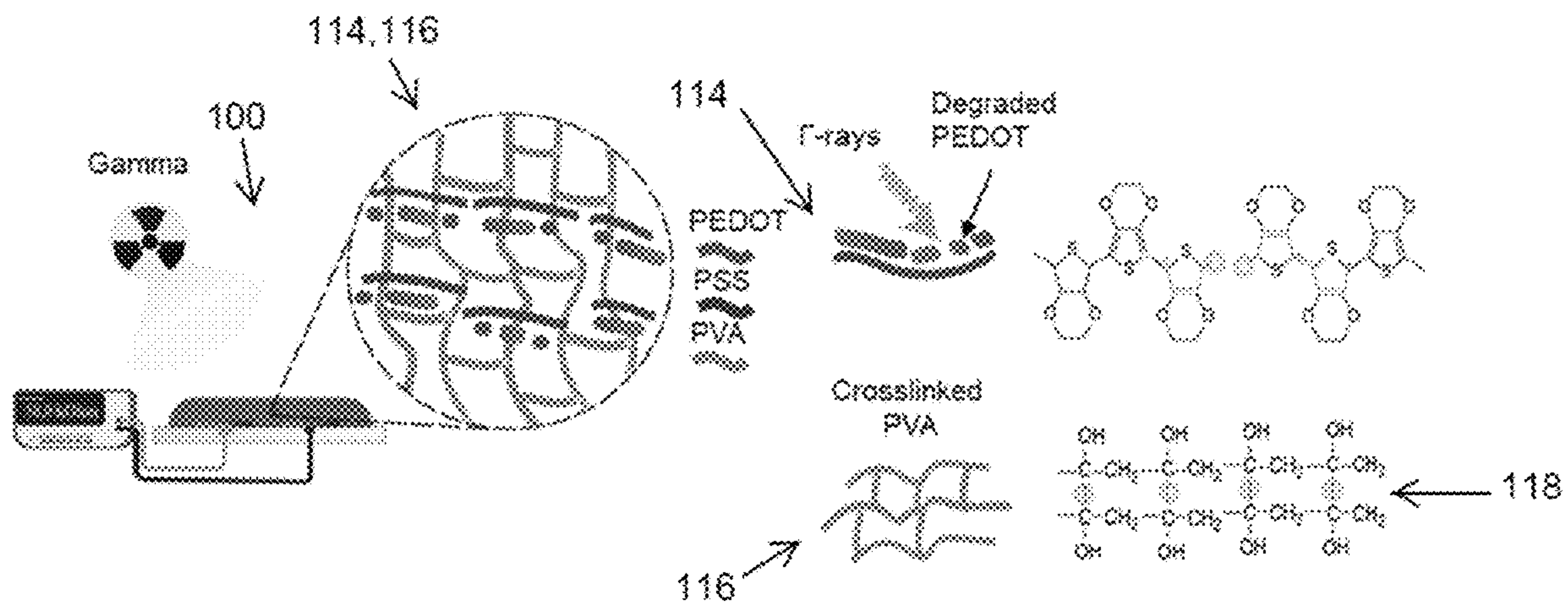


FIG. 1B

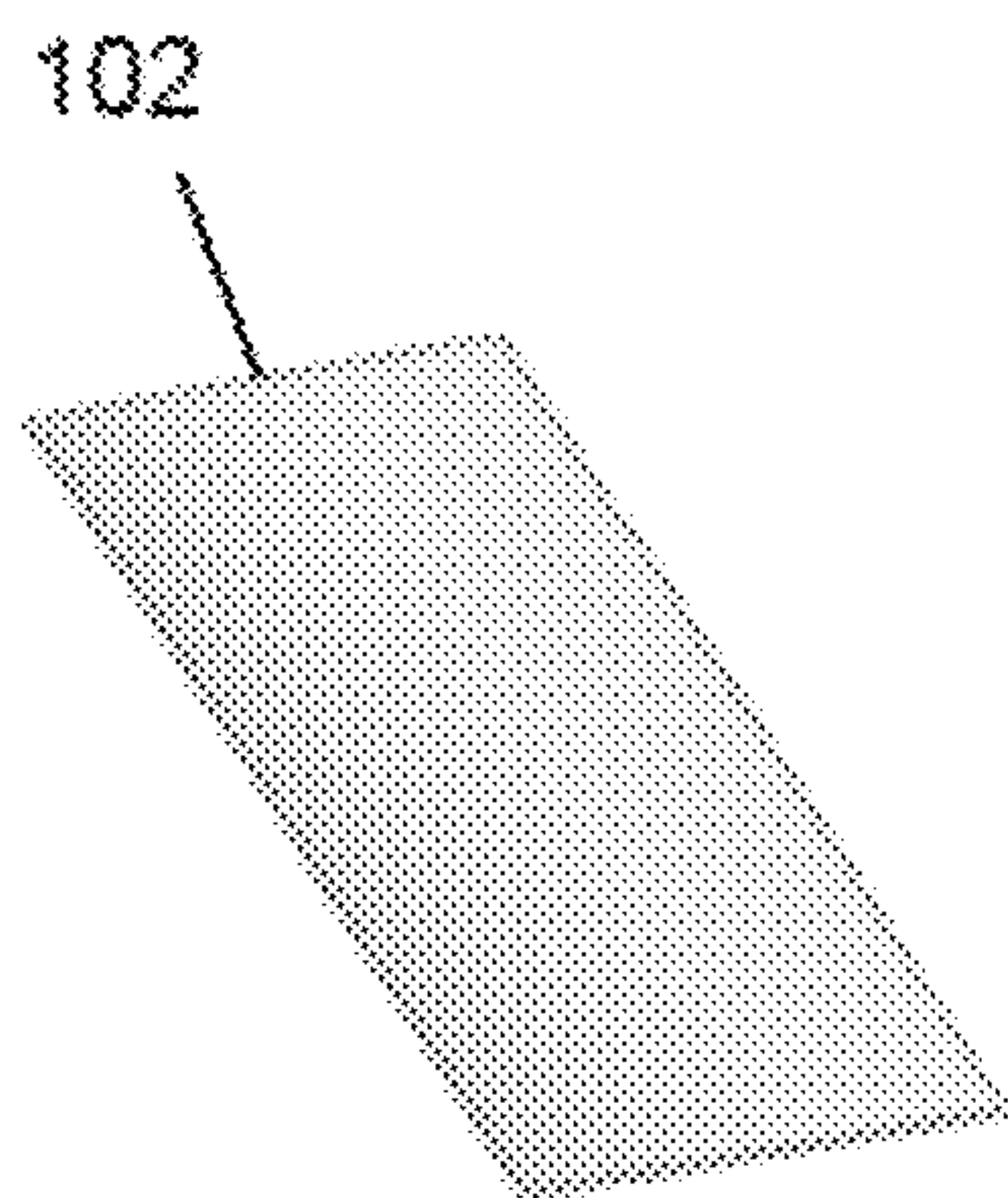


FIG. 2A

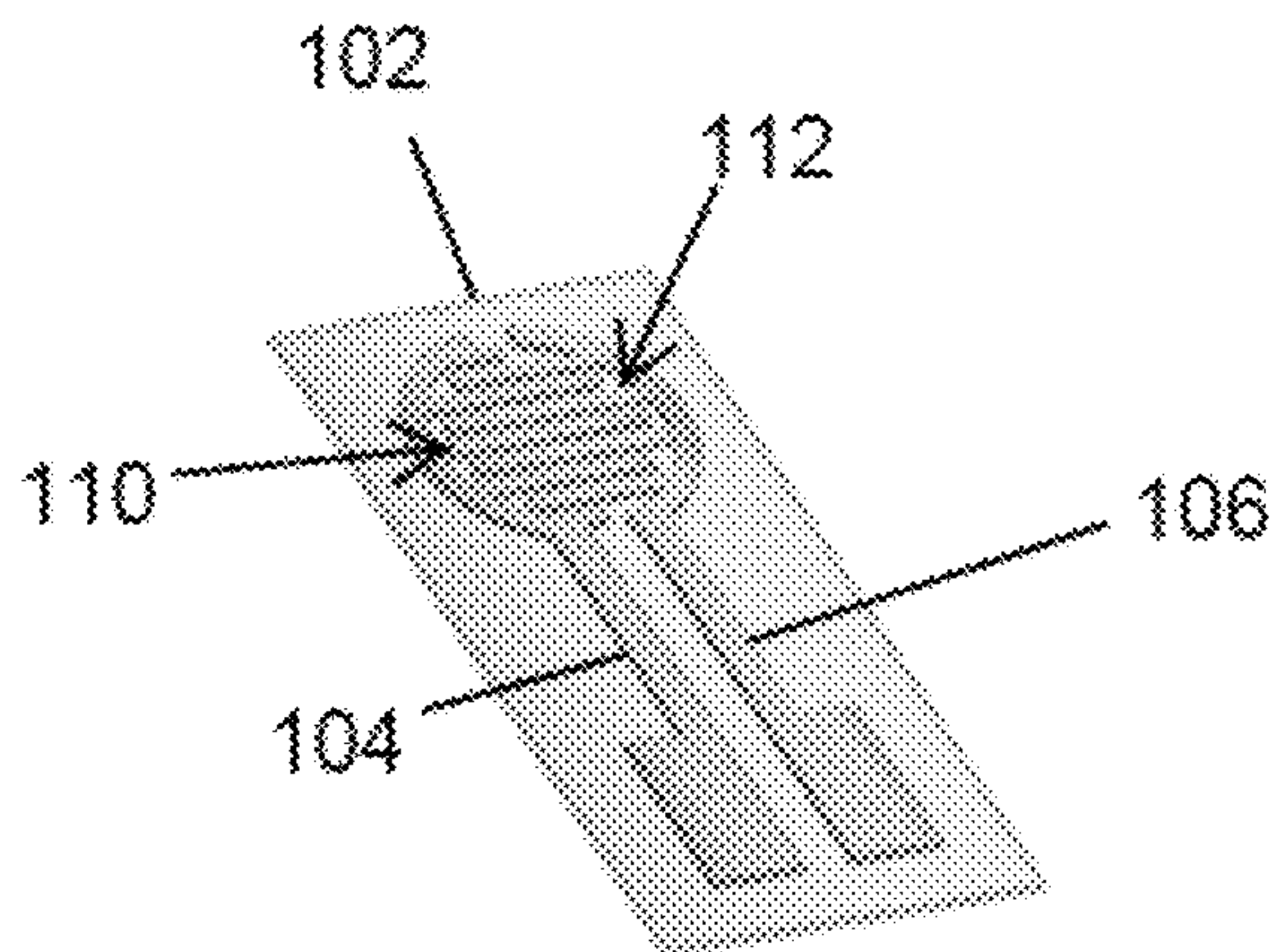


FIG. 2B

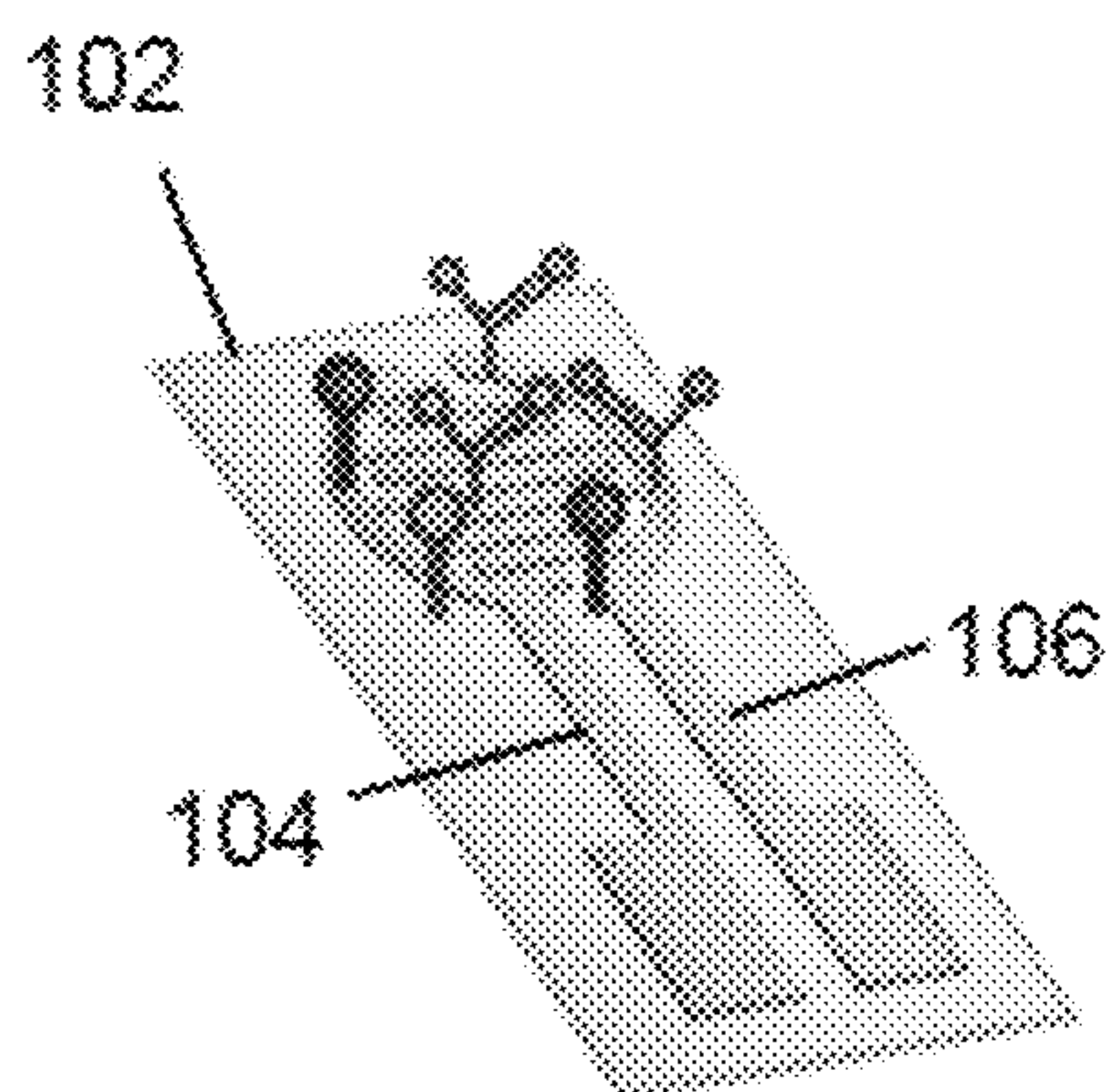


FIG. 2C

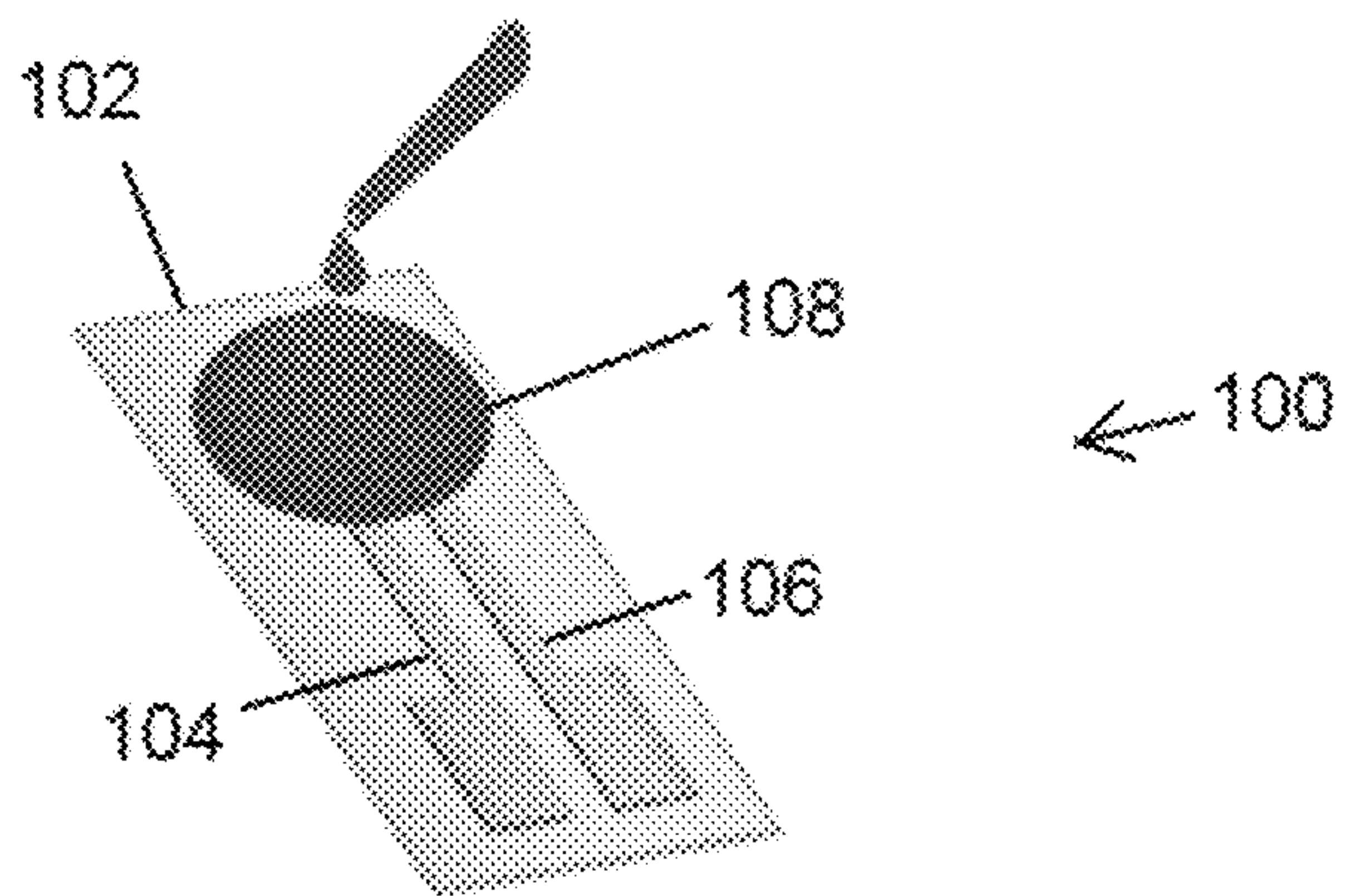


FIG. 2D

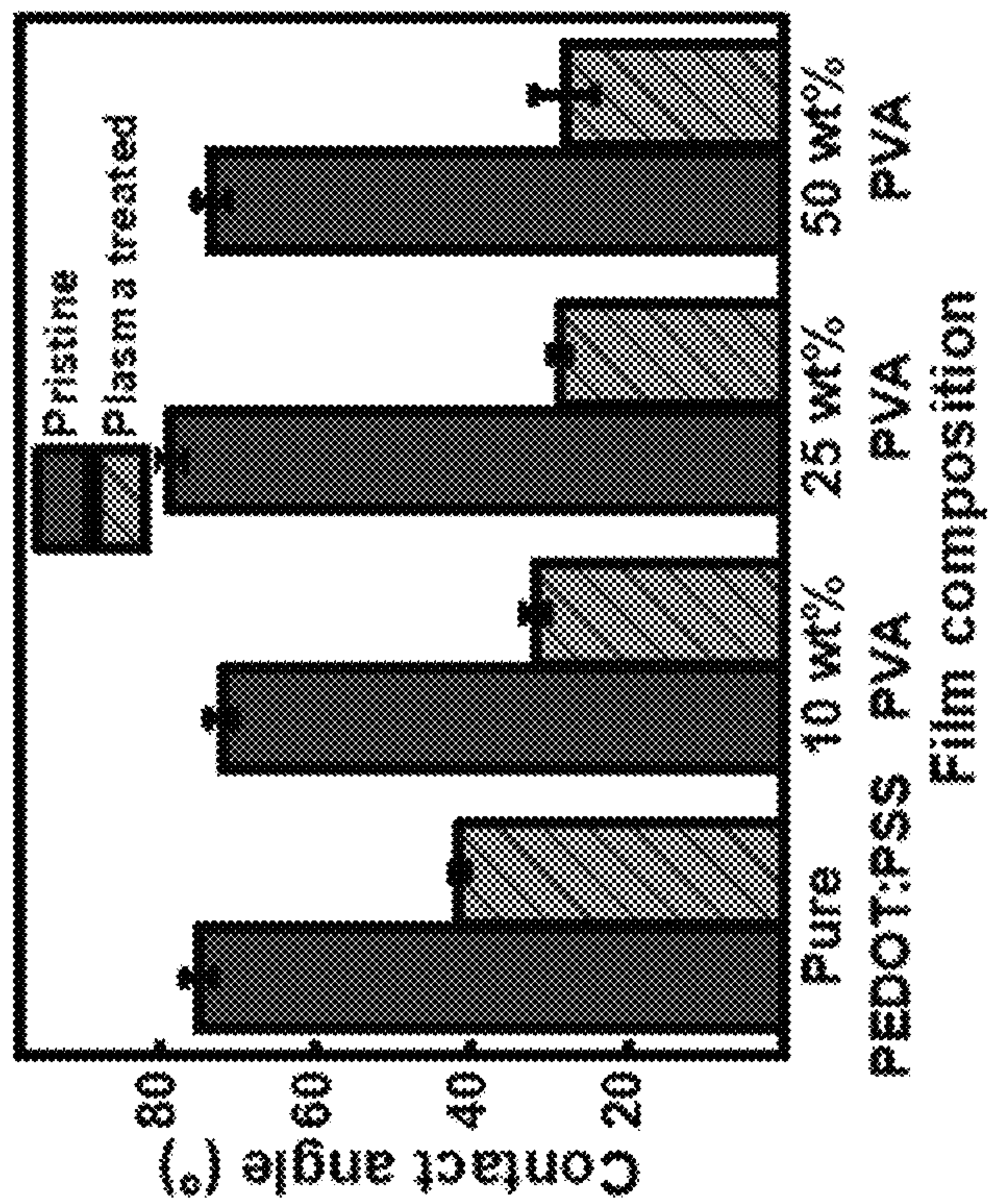
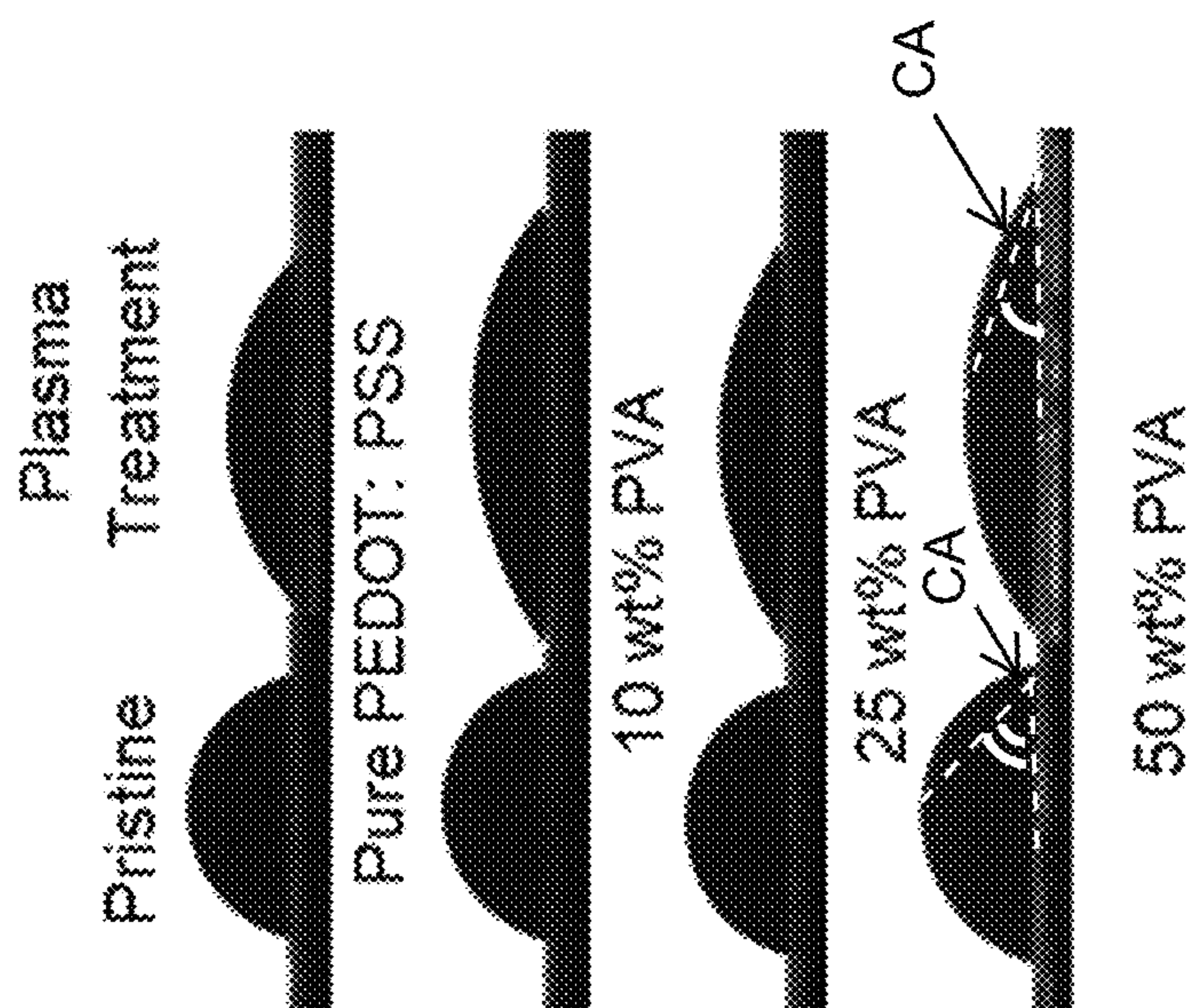


FIG. 3A

FIG. 3B

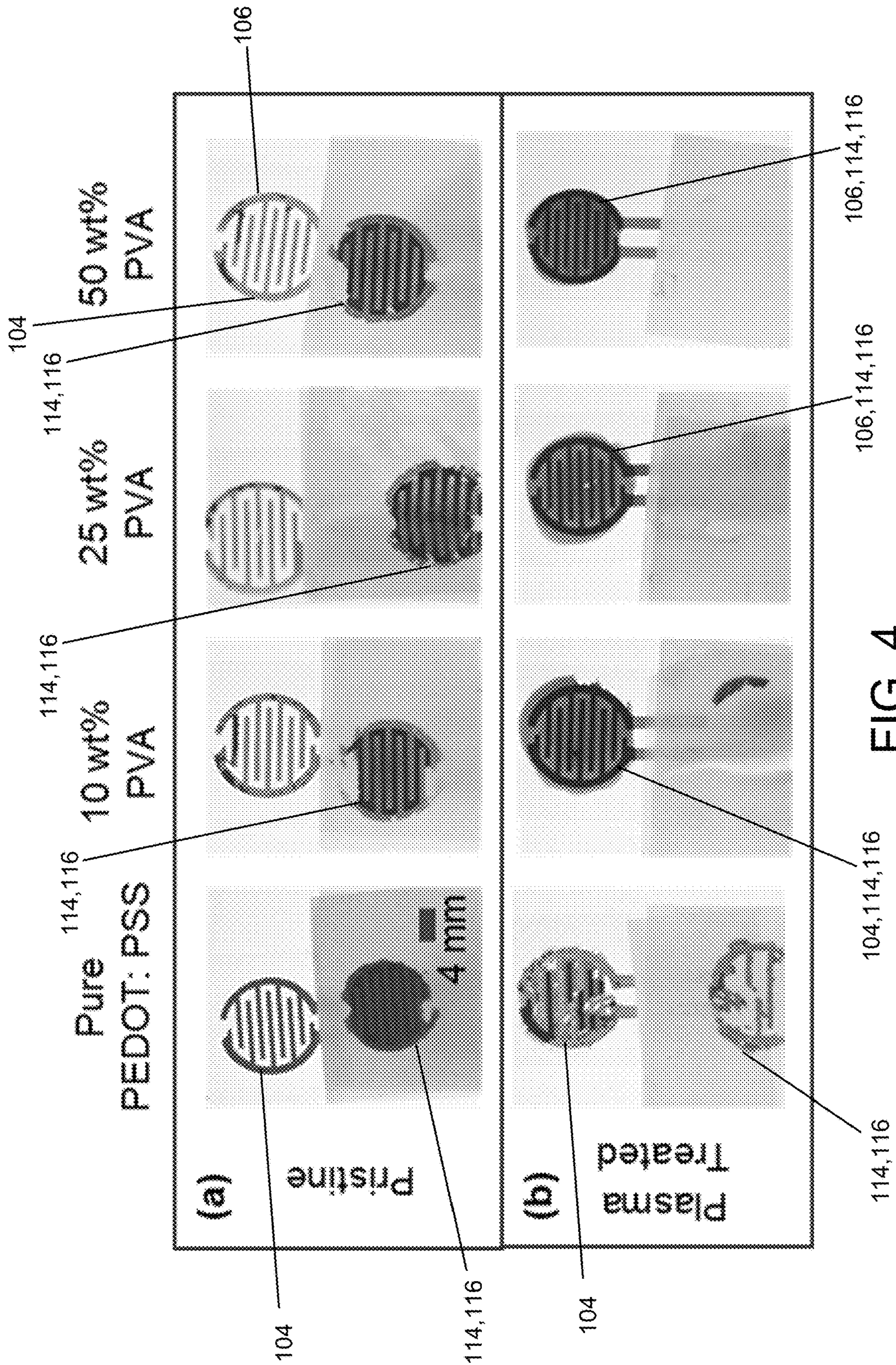


FIG. 4

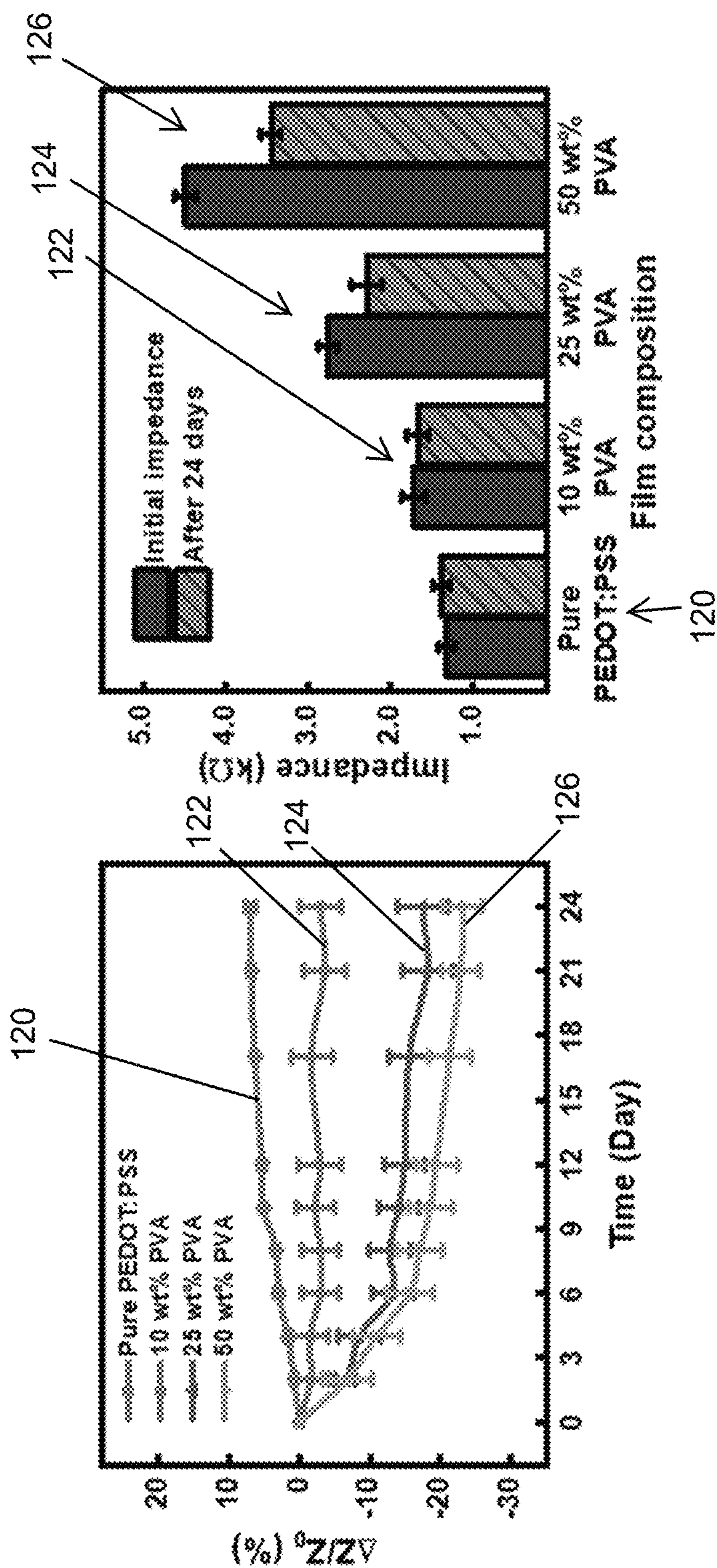


FIG. 5A

FIG. 5B

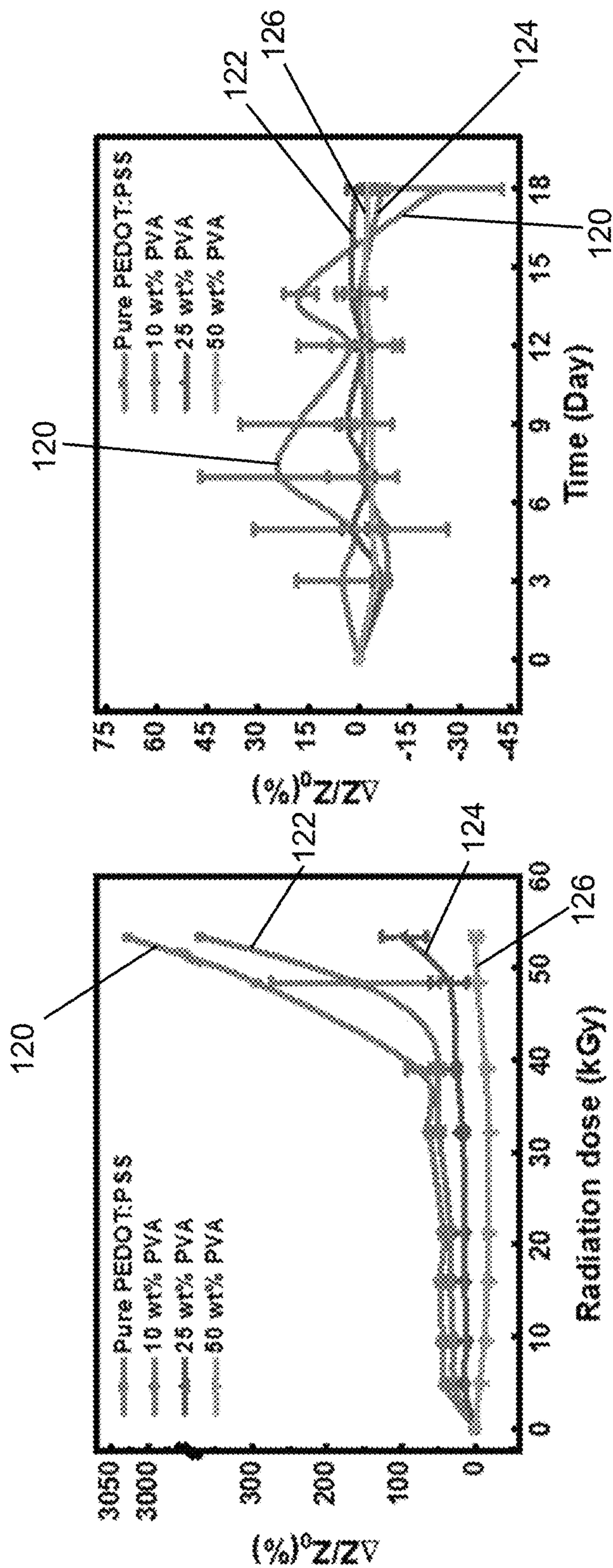


FIG. 6B

FIG. 6A

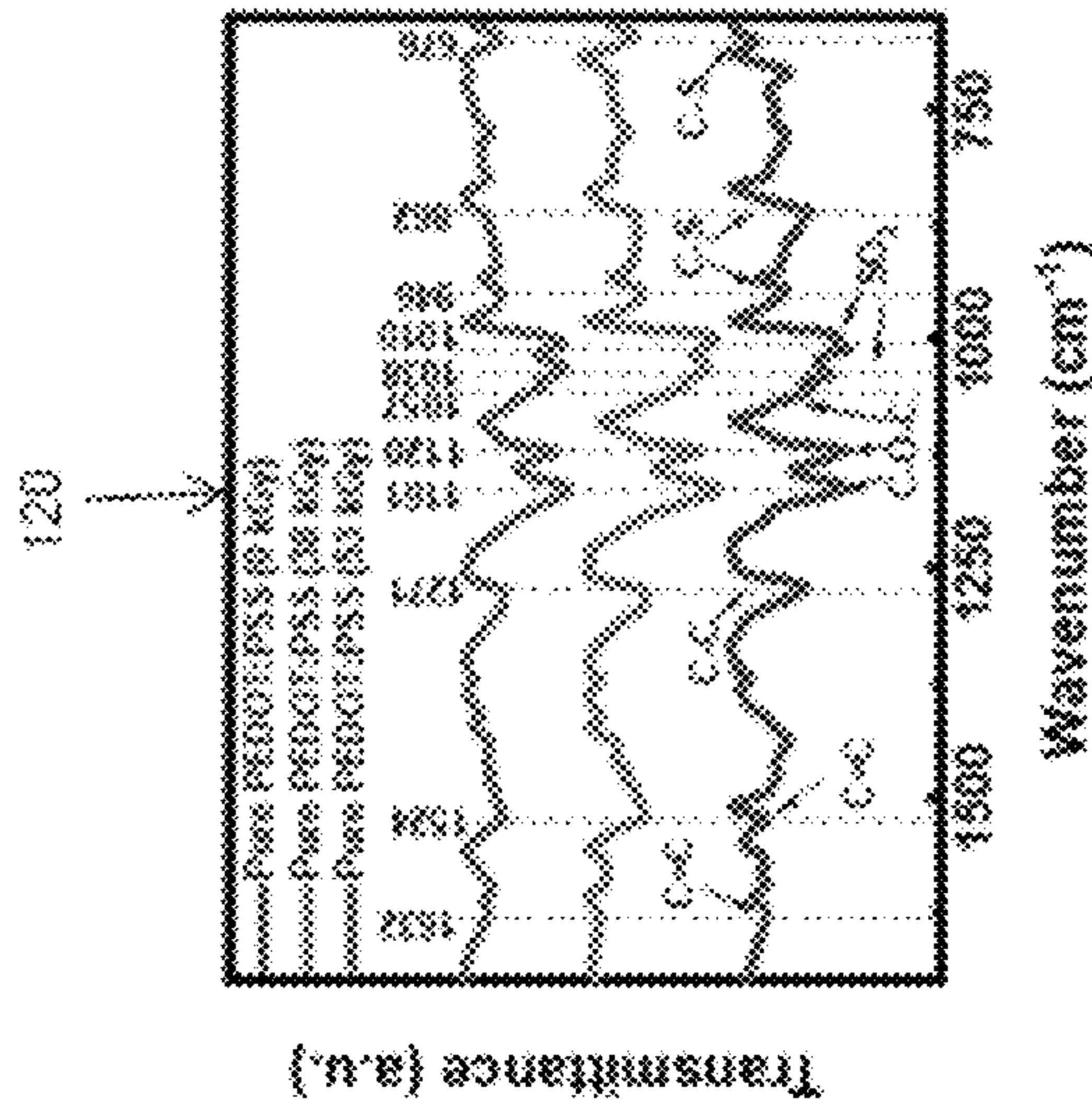


FIG. 7B

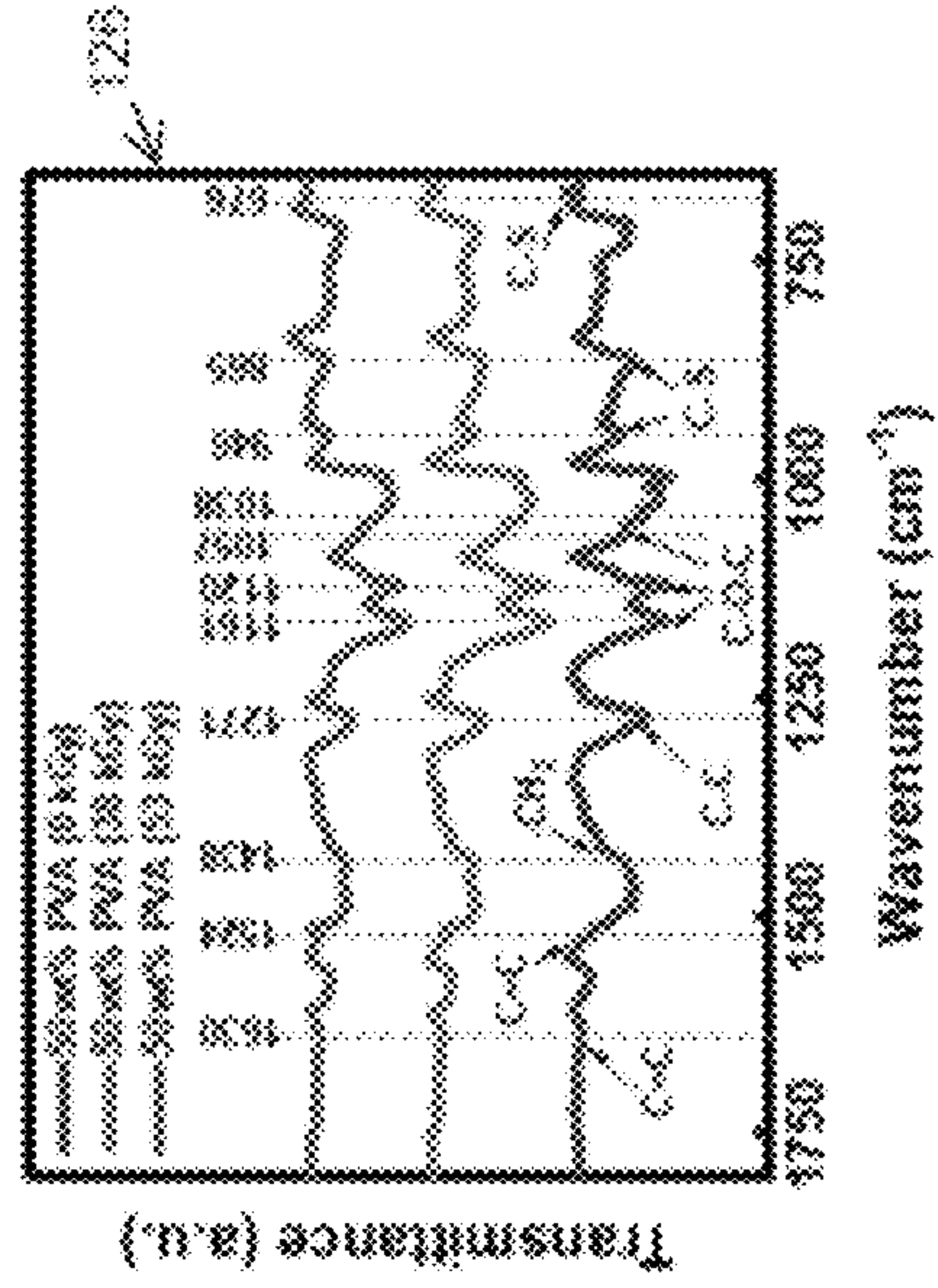


FIG. 7D

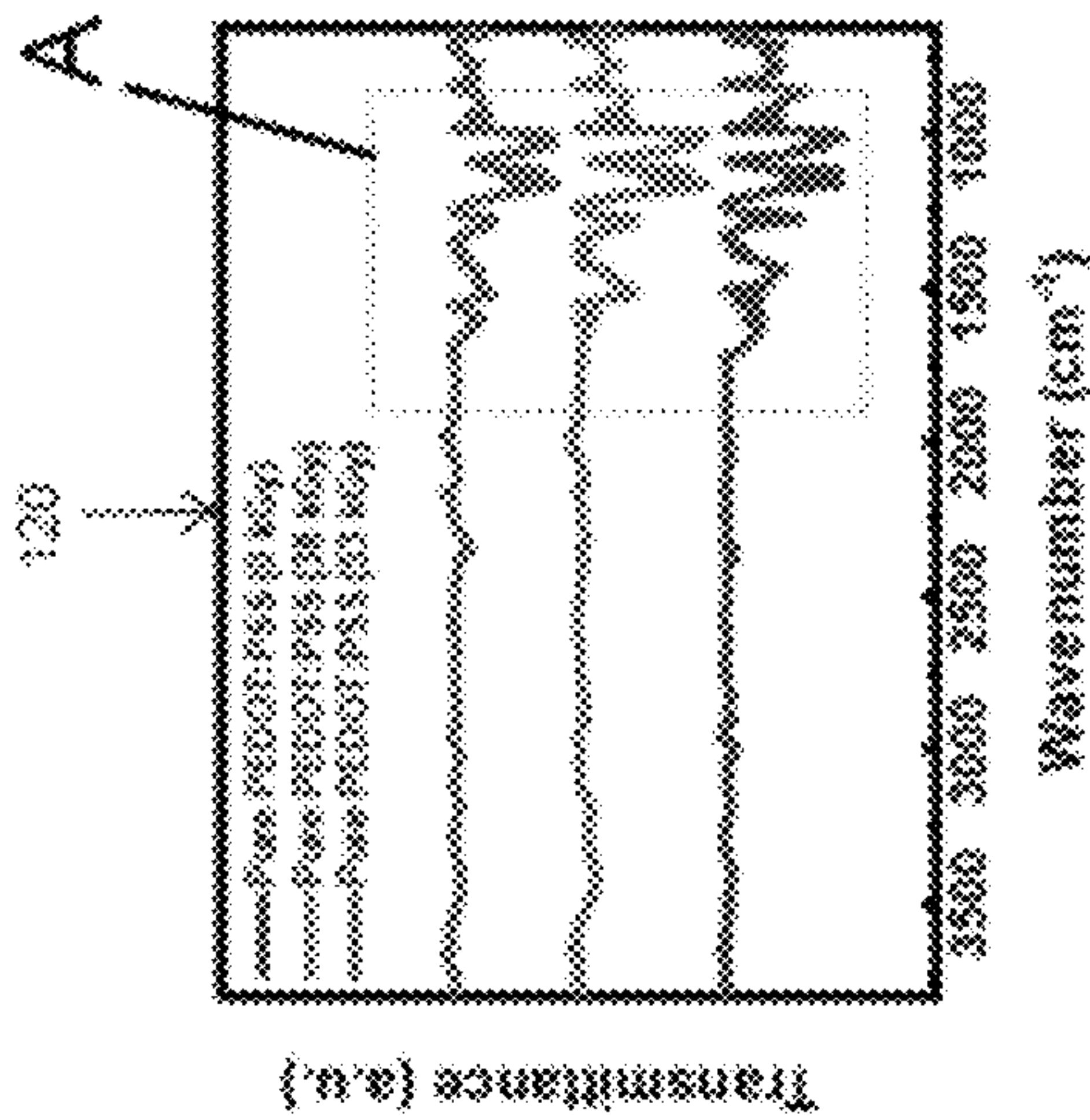


FIG. 7A

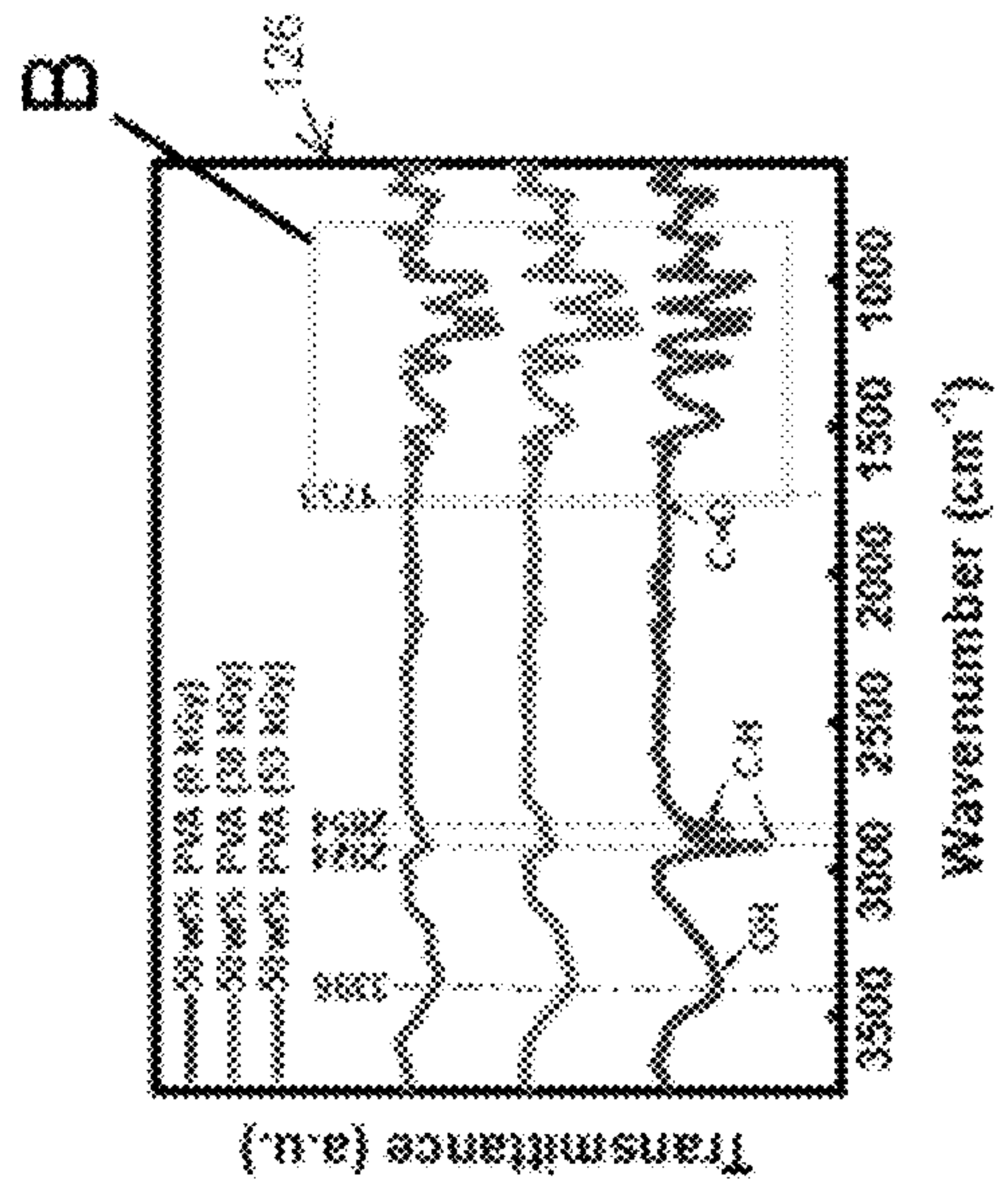


FIG. 7C

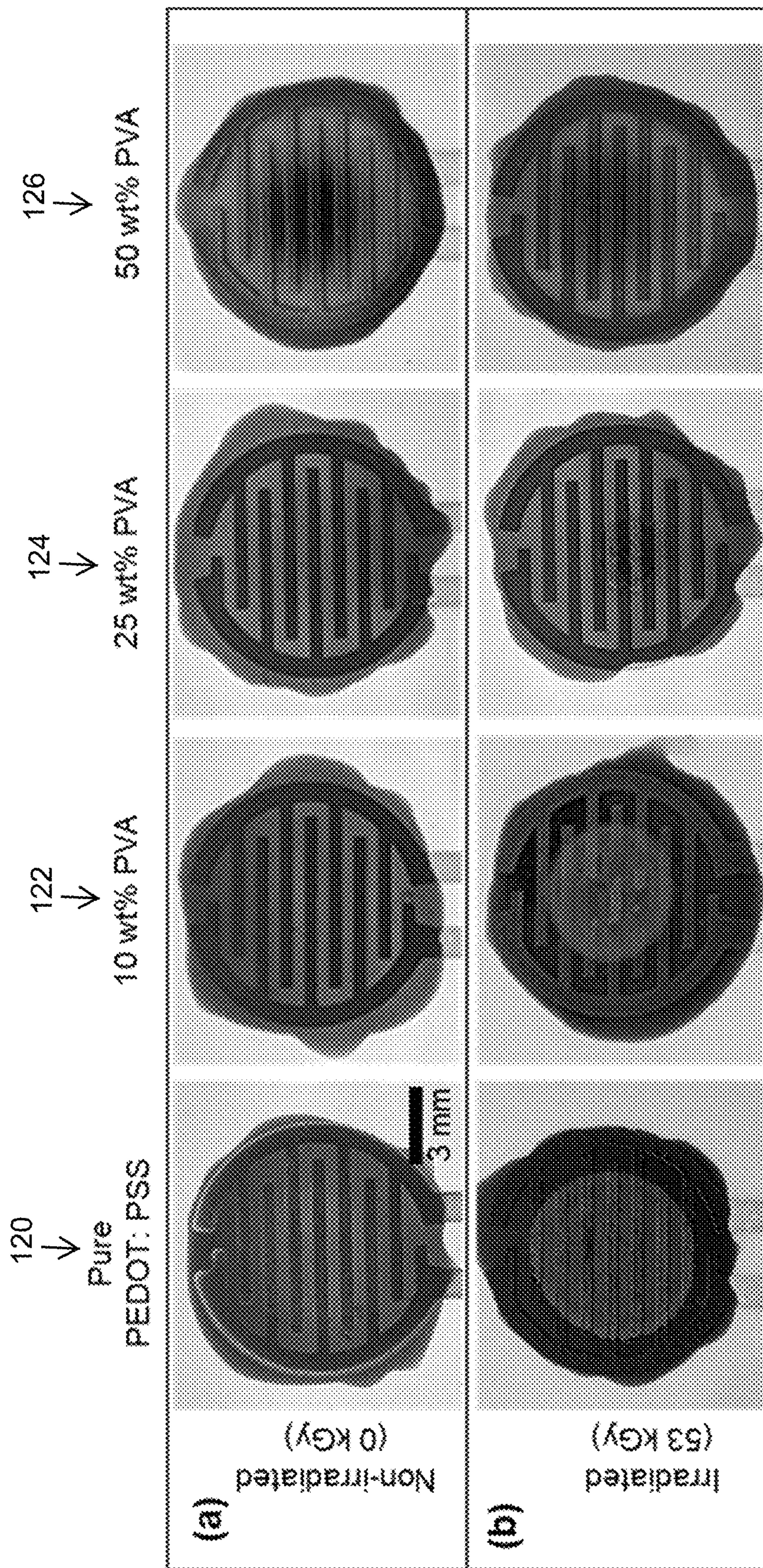


FIG. 8

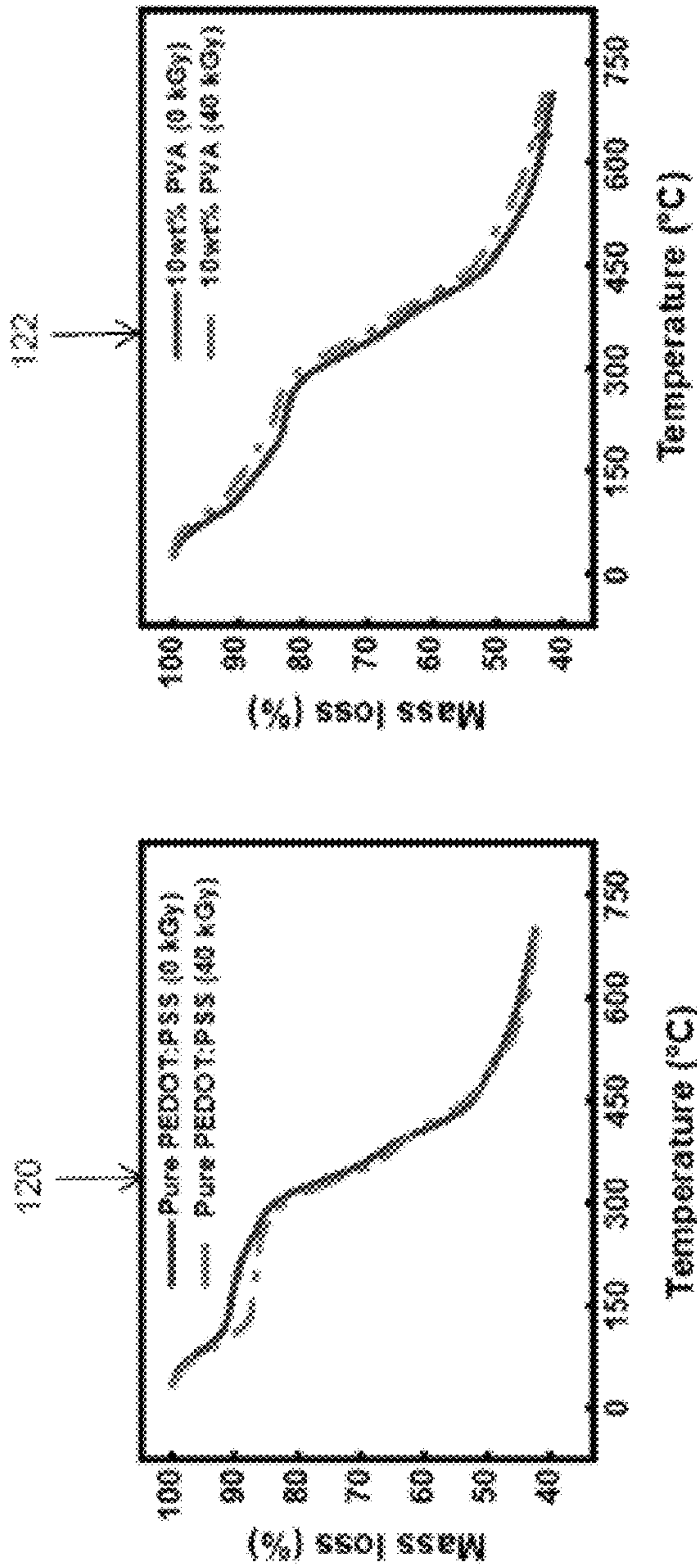


FIG. 9A

FIG. 9B

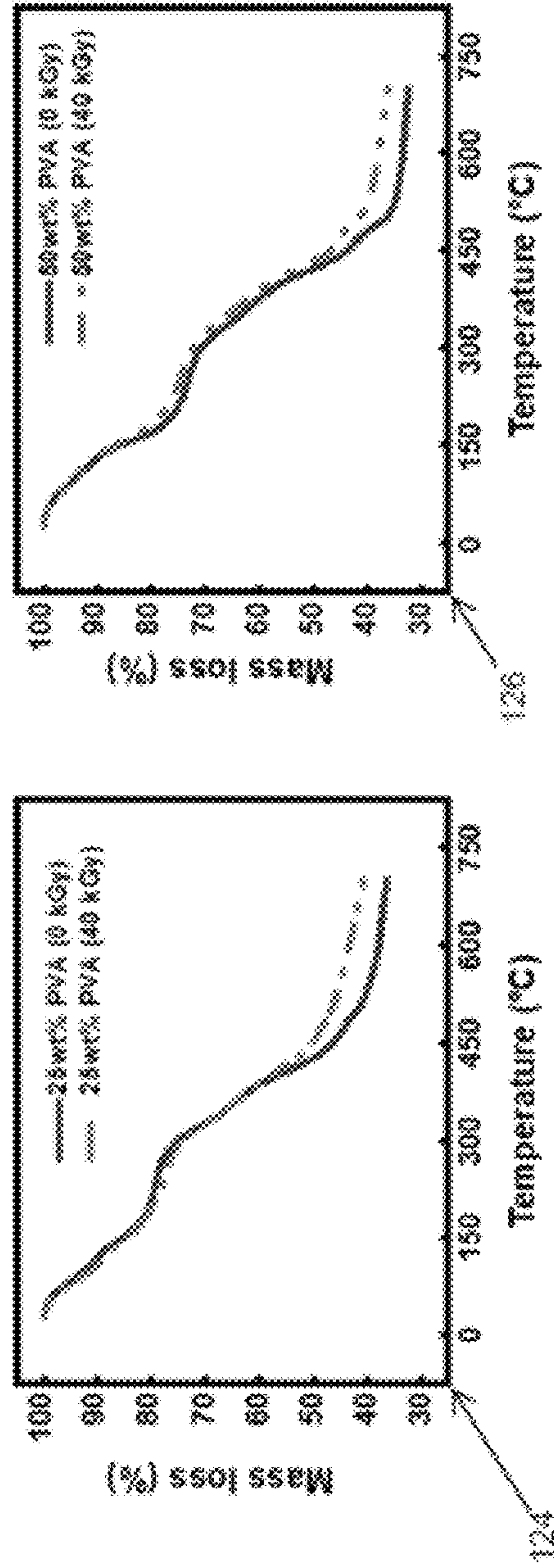


FIG. 9C

FIG. 9D

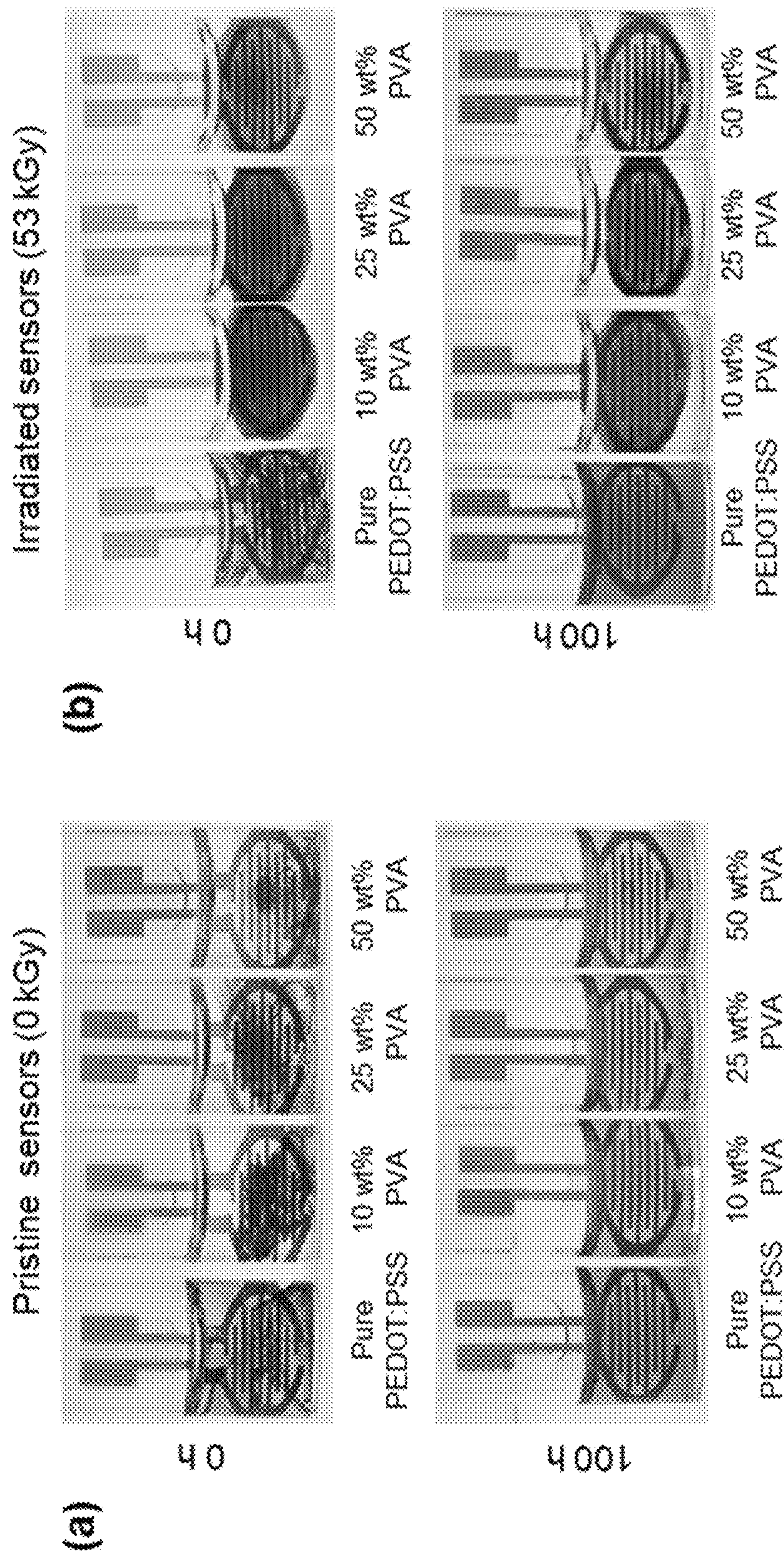


FIG. 10

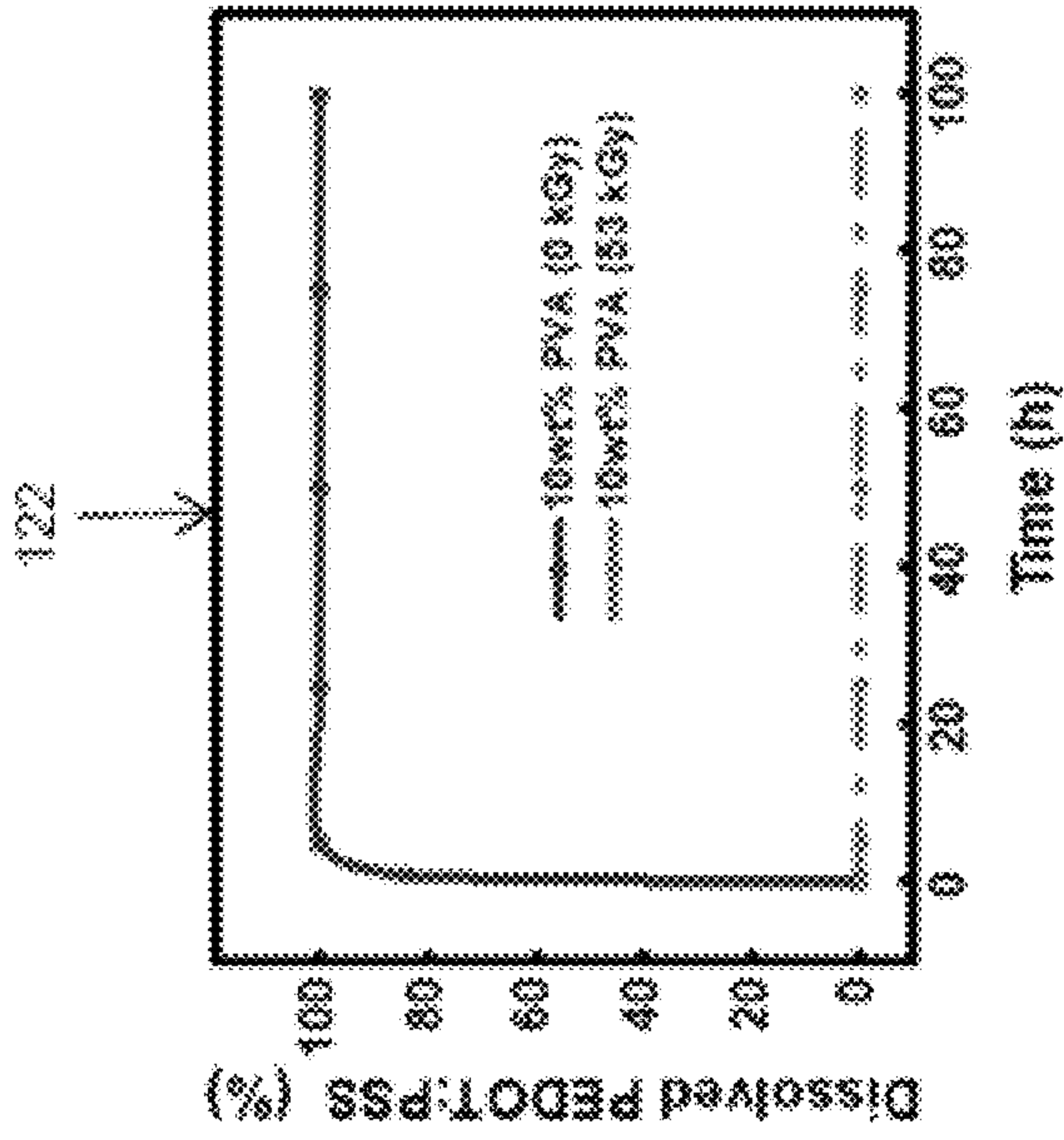


FIG. 11B

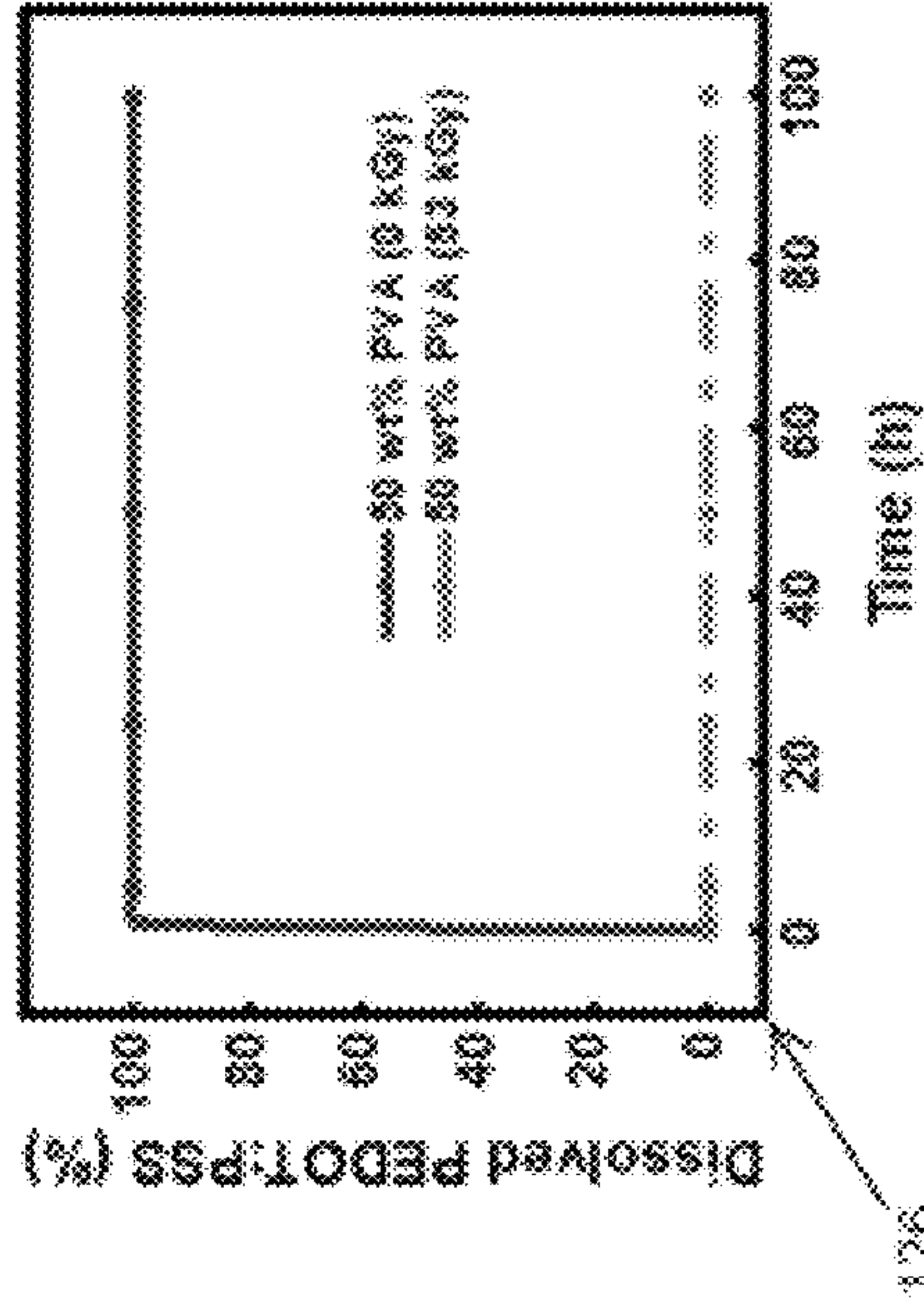


FIG. 11D

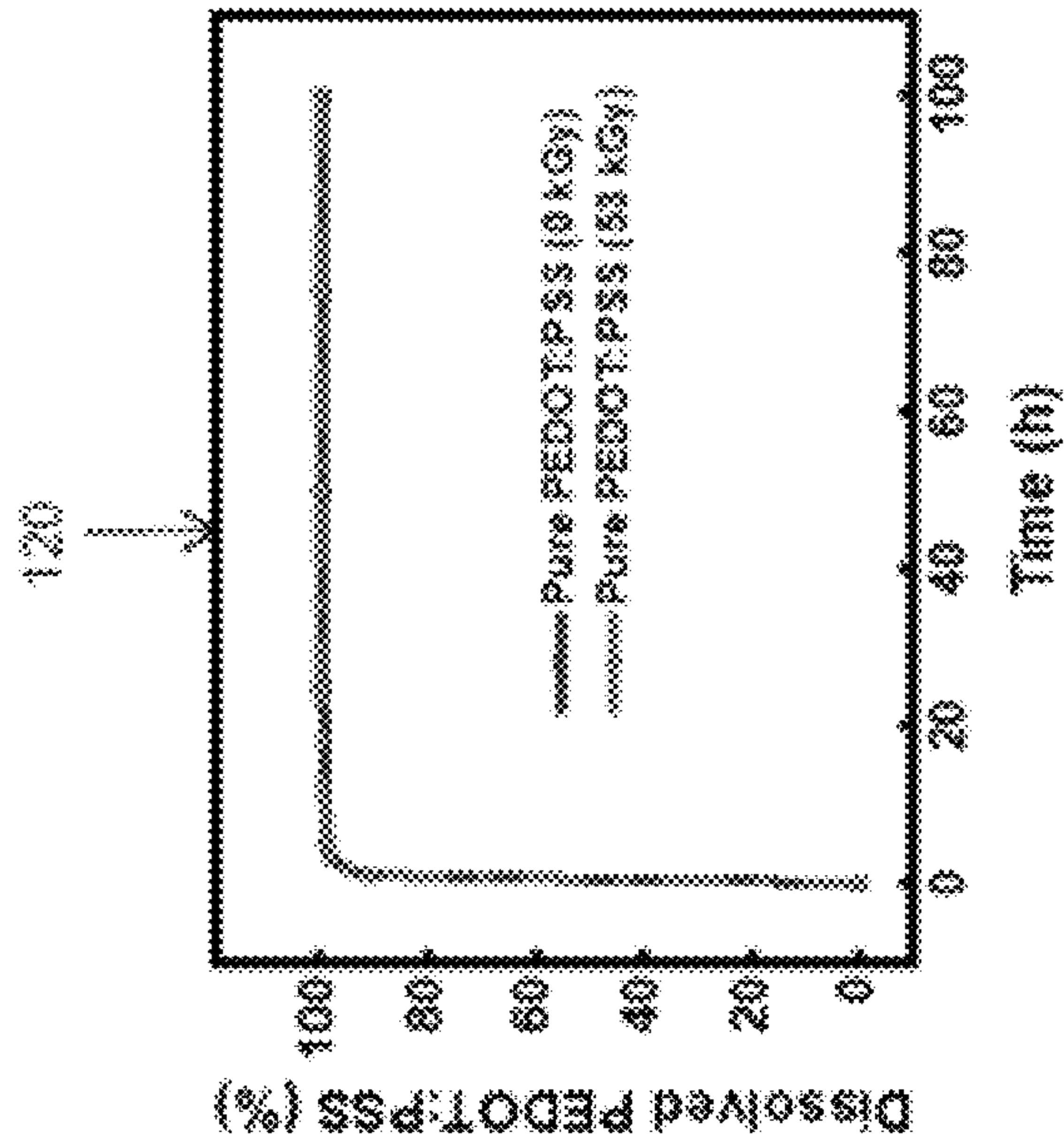


FIG. 11A

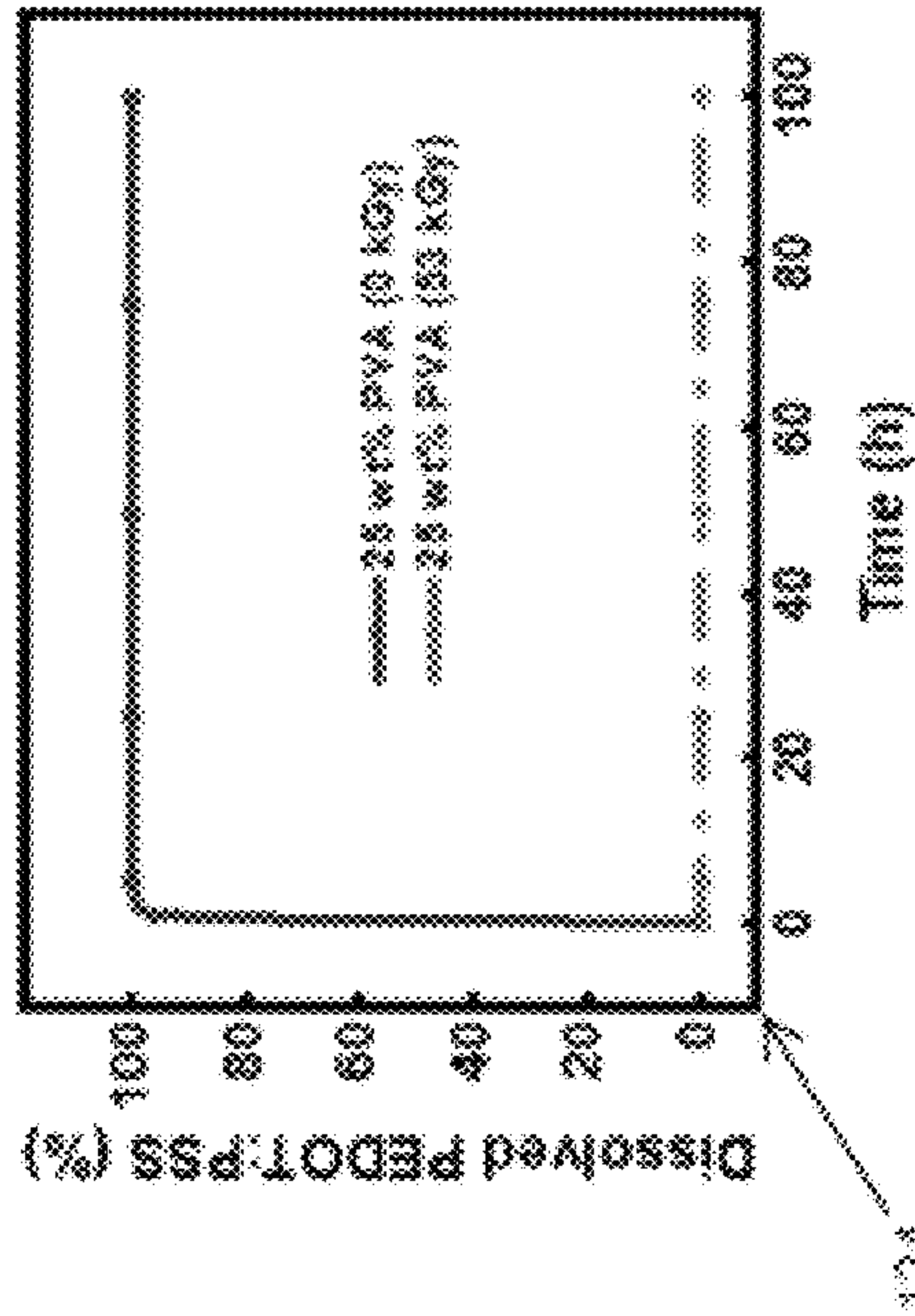
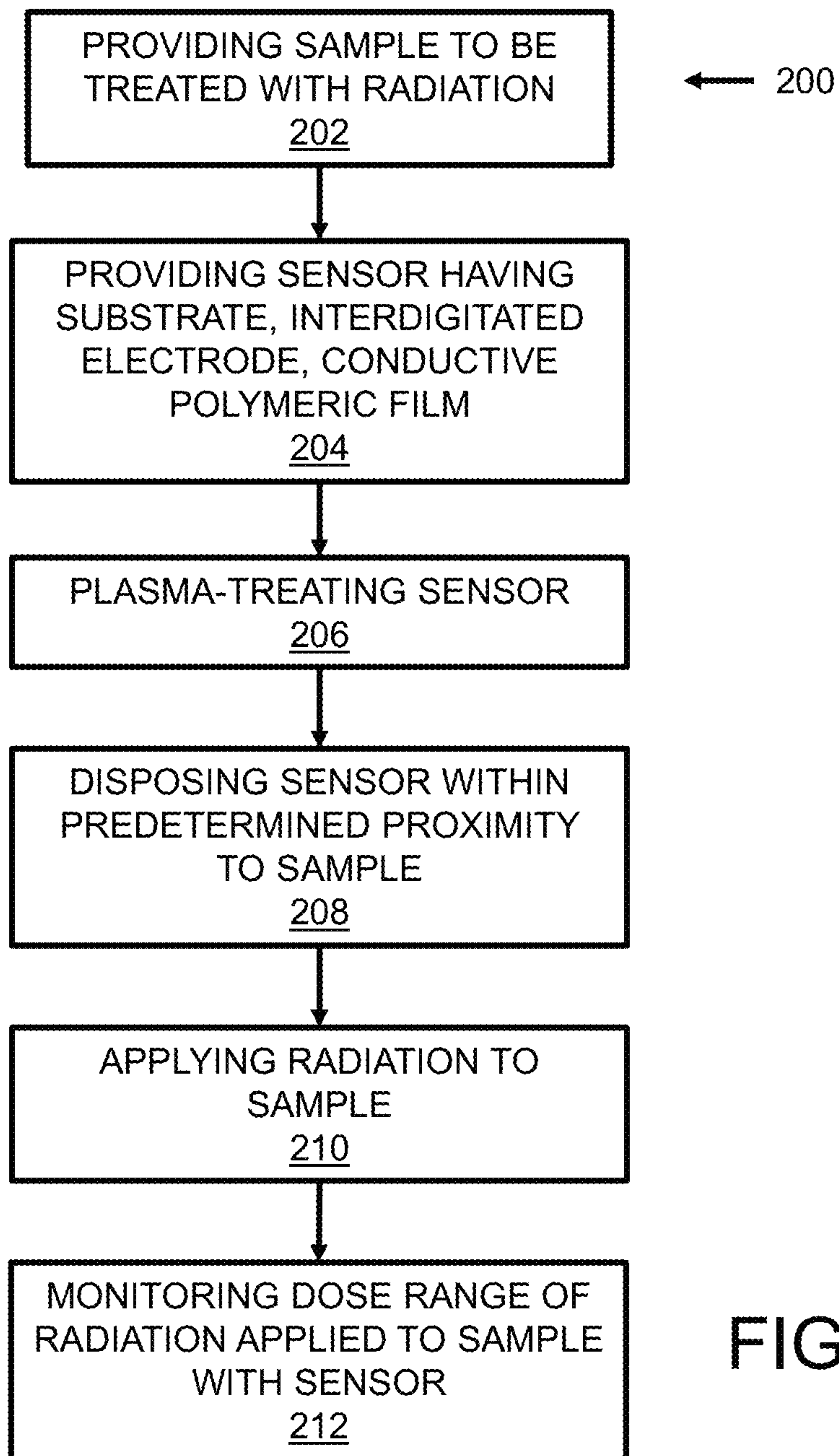


FIG. 11C



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SENSOR SYSTEM AND METHOD FOR GAMMA RADIATION DOSE MEASUREMENT

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application Ser. No. 63/134,276, filed on Jan. 6, 2021. The entire disclosure of the above application is hereby incorporated herein by reference.

FIELD

The present disclosure relates to sensors and, more particularly, to gamma radiation sensors.

INTRODUCTION

This section provides background information related to the present disclosure which is not necessarily prior art.

According to the latest disinfection and sterilization guidelines published by U.S. Centers for Disease Control and Prevention (CDC) for medical facilities, around ~47 million surgical and invasive medical procedures are performed annually. These procedures include unavoidable contact by a surgical instrument or medical device with the patient's mucous membrane, vascular system, and/or sterile tissue. The use of infected or unsterilized medical equipment for another patient transports not only a threat related with breach of host barriers but also the risk for human-to-human spread of various illnesses, such as Coronavirus Disease-2019 (Covid-19) and hepatitis uB virus, provided as non-limiting examples. Therefore, to militate against the surgical or medical instruments from transmitting infectious pathogens to patients, as well as to stop the spread of ongoing Covid-19, proper sterilization and cleaning of all pharmaceutical equipment (e.g., reusable, and single-use bioreactors) and food is extremely important and essential. Sterilization should be understood as a process used to effectively kill or inactivate harmful microorganisms (e.g., microbes and viruses) present on a specific surface.

The conventional sterilization methods fall into one of the following categories: thermal sterilization, radiation sterilization, chemical sterilization, and filtration. Many single use medical devices, such as syringes, surgical gloves, masks, and personal protective equipment (PPE), are chemical and temperature sensitive, which makes the radiation sterilization method a preferred method over thermal and chemical sterilization processes. Moreover, as seen during the Covid-19 pandemic, when there is a large demand for proper sterilization of single use items (such as masks and PPE kits) at a rapid scale, a fast radiation sterilization method is preferred over the slower thermal and chemical sterilization processes. Additionally, radiation sterilization offers competitive advantages over other sterilization methods such as enhanced penetration, heightened certainty of sterility, and enhanced effectiveness independent of temperature and pressure conditions. Radiation sterilization can also be used for sterilization of a final packed product ensuring that the irradiated product remains sterile until the product is removed from the package.

Despite the several benefits of radiation sterilization, it also has the downside of requiring proper monitoring of the dosage that is applied to the package or medical device. In particular, when gamma radiation is used to sterilize polymer-based products, significant attention should be given to

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avoid over-exposure and under-exposure of the product. High radiation exposure may lead to deleterious effects on the chemical and mechanical characteristics of materials and may create toxic compounds. Polymer degradation via crosslinking and chain scission may occur simultaneously in polymers at high radiation doses. Conversely, under-exposure may result in the ineffective eradication of pathogens such as bacteria and viruses on the medical device. Therefore, to avoid the over-exposure and under-exposure of medical devices to gamma radiation, effective monitoring of radiation sterilization processes is important.

Many radiation sterilization facilities often require stacking packaged medical instruments in large tote containers. Due to the high variability in terms of packaged medical instruments and the material used in their fabrication, there can be large variability between levels of exposure that each packaged instrument may receive in this process. Therefore, it is a critical need to have distributed sensors attached to each packaged instrument inside the container that can measure the received dosage of each package after the radiation sterilization process. Currently, two types of known dosimeters (active and passive) have been used for the radiation detection. Active technology commonly utilizes some form of solid-state electronic device that measures the amount of ionizing radiation present in their environment, which can be interfaced with a readout device. These active devices are often too costly for use in such sterilization processes and thus, their use is limited to wearable dosimeter applications for occupational monitoring applications by personnel in nuclear and hospital facilities. Passive based technologies are often based on colorimetric methods where a sensing compound changes color with exposure to radiation. In spite of their simplicity, they often require costly UV spectroscopy machinery for measurement, as well as suffering from high variability and low sensitivity. Hence, there remains a need to develop an adequately sensitive, low cost, and easy to use platform for monitoring the radiation sterilization process.

Recently, conducting polymers have been extensively used for the development of printed low-cost sensors including humidity, temperature, pH, strain, and gas sensors. Even more recently, due to unique changes exhibited by conducting polymers in their electrical properties upon exposure to ionizing radiation, these polymers have also been used for radiation sensing. For instance, Pacheco et al., 2003, *Polyaniline/poly acid acrylic thin film composites: A new gamma radiation detector*, Mater. Charact. 50, 245-248, developed thin films based on polyaniline/poly acid acrylic (PANI/PAA) composites for gamma radiation detection. Bodugöz et al., 2005, *Radiation induced dehydrochlorination as an in-situ doping technique for enhancement of the conductivity of polyaniline blends*, Nucl. Instruments Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms. 236, 153-159, studied the in-situ radiation-induced acid doping process of polyaniline/poly(vinyl) chloride (PANI/PVC) composites. Further, Kane et al., 2010, *Investigation on the effects of beta and gamma irradiation on conducting polymers for sensor applications*, Radiation Physics and Chemistry 79, 1189-1195, reported the effects of ionizing radiation on the PEDOT-based materials to gamma and beta radiation doses between 10 Gray and 107 Gray. However, the changes in conductivity using PEDOT:PSS alone is erratic and ill-suited for sensor applications. Despite the substantial progress in the radiation sensors using conducting polymers,

there is a continuing need to develop a low-cost, flexible, portable, and printed dosimeter at a large scale.

SUMMARY

In concordance with the instant disclosure, a radiation sensing system and method that enhances the certainty of adequate sterility and that may be manufactured more efficiently over known radiation sensors, has been surprisingly discovered.

In one embodiment, a radiation sensor includes a substrate, an electrode, and a conductive polymeric film. The substrate may be flexible. The electrode may be an interdigitated electrode including a first electrode with a plurality of first electrode digits and a second electrode with a plurality of second electrode digits. The interdigitated electrode may be disposed on the substrate. The conductive polymeric film may include a blend of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) and polyvinyl alcohol (PVA). The conductive polymeric film may be disposed on and/or between the first electrode and the second electrode. The radiation sensor may include an all-printed sensor that utilizes a mixer of PVA and PEDOT:PSS as the active radiation sensing material. The PEDOT:PSS may act as the electrically conductive medium, while the PVA may advantageously provide ductility and stability of the printed sensor. Upon radiation exposure, the PVA may crosslink within a material matrix of the printed radiation sensor militating against the recombination of chain scission by forming a semi-interpenetrating polymer network (SIPN) with PEDOT:PSS which may result in a more stable impedance reading. Desirably, the radiation sensor may utilize scalable printing technologies which may further permit low-cost manufacturing of the radiation sensor at large scale.

In another embodiment, the present technology includes methods of using the radiation sensor. For instance, a method of using the radiation sensor may include providing a sample to be treated by a gamma radiation. The method may also include providing a sensor having a substrate, an electrode, and a conductive polymeric film. The substrate may be flexible. The electrode may be an interdigitated electrode including a first electrode with a plurality of first electrode digits and a second electrode with a plurality of second electrode digits. The interdigitated electrode may be disposed on the substrate. The conductive polymeric film may include a blend of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) and polyvinyl alcohol (PVA). The conductive polymeric film may be disposed on and/or between the first electrode and the second electrode. Next, the method may include disposing the sensor within a predetermined proximity to the sample. Afterwards, gamma radiation may be applied to the sample. The method may further include monitoring a dose range of the gamma radiation applied to the sample with the sensor.

Further areas of applicability will become apparent from the description provided herein. It should be understood that the description and specific examples are intended for purposes of illustration only and are not intended to limit the scope of the present disclosure.

DRAWINGS

The drawings described herein are for illustrative purposes only of selected embodiments and not all possible implementations and are not intended to limit the scope of the present disclosure.

FIG. 1(a) is a schematic diagram of a sensor including a poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) and polyvinyl alcohol (PVA) blend composite before irradiation, according to one embodiment of the present disclosure;

FIG. 1(b) is a schematic diagram of the sensor including a PEDOT:PSS/PVA composite, as shown in FIG. 1(a), after irradiation, further depicting the PVA crosslinked which may then hold the PEDOT:PSS chains in place after scission, according to one embodiment of the present disclosure;

FIG. 2(a) is a schematic diagram of a substrate of the sensor, according to one embodiment of the present disclosure;

FIG. 2(b) is a schematic diagram of an interdigitated electrode disposed on the substrate, as shown in FIG. 2(a), according to one embodiment of the present disclosure;

FIG. 2(c) is a schematic diagram of an interdigitated electrode being plasma-treated on the substrate, as shown in FIGS. 2(a)-2(b), according to one embodiment of the present disclosure;

FIG. 2(d) is a schematic diagram of the PEDOT:PSS/PVA composite forming a conductive polymeric film on the interdigitated electrode and the substrate, as shown in FIGS. 2(a)-2(c), according to one embodiment of the present disclosure;

FIG. 3(a) is a schematic diagram illustrating a contact angle of the conductive polymeric film where the sensor is plasma-treated in comparison to where the sensor is non-plasma-treated, and further depicting the contact angle where the conductive polymeric film does not include PVA in comparison to where varying amounts of PVA are included, according to one embodiment of the present disclosure;

FIG. 3(b) is a bar graph illustrating the quantified average contact angles in the comparisons shown in FIG. 3(a), according to one embodiment of the present disclosure;

FIG. 4 is a schematic diagram, illustrating adhesion test results of the conductive polymeric film to the interdigitated electrode where the sensor was non-plasma-treated in comparison to where the sensor was plasma-treated;

FIG. 5(a) is a line graph depicting the relative impedance change over time until reaching stability of the sensor when no PVA is included in the conductive polymeric film in comparison to when varying amounts of PVA is included in the conductive polymeric film, according to one embodiment of the present disclosure;

FIG. 5(b) is a bar graph illustrating the relative impedance change of the sensor from the day of manufacturing compared to the relative impedance change of the sensor at twenty-four days after manufacturing, further depicting the difference in relative impedance change over time when no PVA is included in the conductive polymeric film in comparison to when varying amounts of PVA is included in the conductive polymeric film;

FIG. 6(a) is a line graph depicting the sensitivity of the sensor to varying doses of gamma radiation when no PVA is included in the conductive polymeric film in comparison to when varying amounts of PVA is included in the conductive polymeric film, according to one embodiment of the present disclosure;

FIG. 6(b) is a line graph depicting the sensitivity of the sensor over time when a 53 kGy dose of gamma radiation is applied to the sensor when no PVA is included in the conductive polymeric film in comparison to when varying amounts of PVA is included in the conductive polymeric film, according to one embodiment of the present disclosure;

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FIG. 7(a) is a line graph illustrating the FTIR analysis of a non-irradiated sensor when no PVA is included in the conductive polymeric film in comparison to sensors irradiated with varying doses of radiation that also do not have PVA included in the conductive polymeric film, according to one embodiment of the present disclosure;

FIG. 7(b) is an enlarged view of call-out A, as shown in FIG. 7(a), illustrating the FTIR analysis of a non-irradiated sensor when no PVA is included in the conductive polymeric film in comparison to sensors irradiated with varying doses of radiation that also do not have PVA included in the conductive polymeric film, according to one embodiment of the present disclosure;

FIG. 7(c) is a line graph illustrating the FTIR analysis of a non-irradiated sensor where the conductive polymeric film includes fifty weight percent PVA in comparison to sensors irradiated with varying doses of radiation where the conductive polymeric film also includes fifty weight percent PVA, according to one embodiment of the present disclosure;

FIG. 7(d) is an enlarged view of call-out B, as shown in FIG. 7(c), illustrating the FTIR analysis of a non-irradiated sensor where the conductive polymeric film includes fifty weight percent PVA in comparison to sensors irradiated with varying doses of radiation where the conductive polymeric film also includes fifty weight percent PVA, according to one embodiment of the present disclosure;

FIG. 8 is a schematic diagram illustrating the solubility of the sensor in de-ionized water where non-irradiated sensors are compared to irradiated sensors and where varying amounts of PVA included in the conductive polymeric film is compared to where no PVA is included in the conductive polymeric film, according to one embodiment of the present disclosure;

FIG. 9(a) is a line graph illustrating a thermogravimetric analysis of the sensor, further depicting a mass loss of a non-irradiated sensor having no PVA in the conductive polymeric film compared to a mass loss of an irradiated sensor also having no PVA in the conductive polymeric film, according to one embodiment of the present disclosure;

FIG. 9(b) is a line graph illustrating a thermogravimetric analysis of the sensor, further depicting a mass loss of a non-irradiated sensor having ten weight percent PVA in the conductive polymeric film compared to a mass loss of an irradiated sensor also having ten weight percent PVA in the conductive polymeric film, according to one embodiment of the present disclosure;

FIG. 9(c) is a line graph illustrating a thermogravimetric analysis of the sensor, further depicting a mass loss of a non-irradiated sensor having twenty-five weight percent PVA in the conductive polymeric film compared to a mass loss of an irradiated sensor also having twenty-five weight percent PVA in the conductive polymeric film, according to one embodiment of the present disclosure;

FIG. 9(d) is a line graph illustrating a thermogravimetric analysis of the sensor, further depicting a mass loss of a non-irradiated sensor having fifty weight percent PVA in the conductive polymeric film compared to a mass loss of an irradiated sensor also having fifty weight percent PVA in the conductive polymeric film, according to one embodiment of the present disclosure;

FIG. 10 is a schematic diagram illustrating the solubility of the sensor in de-ionized water over time where non-irradiated sensors are compared to irradiated sensors and where varying amounts of PVA included in the conductive polymeric film is compared to where no PVA is included in

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the conductive polymeric film, according to one embodiment of the present disclosure;

FIG. 11(a) is a line graph illustrating the solubility over time of the conductive polymeric film in de-ionized water via ultraviolet-visible spectroscopy, further depicting the complete dissolution of the conductive polymeric film having no PVA in both non-irradiated and irradiated sensors, according to one embodiment of the present disclosure;

FIG. 11(b) is a line graph illustrating the solubility over time of the conductive polymeric film in de-ionized water via ultraviolet-visible spectroscopy, further depicting the complete dissolution of the conductive polymeric film having 10 weight percent PVA in non-irradiated sensors but no dissolution in irradiated sensors having 10 weight percent PVA in the conductive polymeric film, according to one embodiment of the present disclosure;

FIG. 11(c) is a line graph illustrating the solubility over time of the conductive polymeric film in de-ionized water via ultraviolet-visible spectroscopy, further depicting the complete dissolution of the conductive polymeric film having 25 weight percent PVA in non-irradiated sensors but no dissolution in irradiated sensors having 25 weight percent PVA in the conductive polymeric film, according to one embodiment of the present disclosure;

FIG. 11(d) is a line graph illustrating the solubility over time of the conductive polymeric film in de-ionized water via ultraviolet-visible spectroscopy, further depicting the complete dissolution of the conductive polymeric film having 50 weight percent PVA in non-irradiated sensors but no dissolution in irradiated sensors having 50 weight percent PVA in the conductive polymeric film, according to one embodiment of the present disclosure; and

FIG. 12 is a flow chart illustrating a method of using the sensor, according to one embodiment of the present disclosure.

DETAILED DESCRIPTION

The following description of technology is merely exemplary in nature of the subject matter, manufacture and use of one or more inventions, and is not intended to limit the scope, application, or uses of any specific invention claimed in this application or in such other applications as may be filed claiming priority to this application, or patents issuing therefrom. Regarding methods disclosed, the order of the steps presented is exemplary in nature unless otherwise disclosed, and thus, the order of the steps can be different in various embodiments, including where certain steps can be simultaneously performed.

I. Definitions

Unless otherwise defined, all technical terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which the present disclosure pertains.

As used herein, the terms “a” and “an” indicate “at least one” of the item is present; a plurality of such items may be present, when possible. Except where otherwise expressly indicated, all numerical quantities in this description are to be understood as modified by the word “about” and all geometric and spatial descriptors are to be understood as modified by the word “substantially” in describing the broadest scope of the technology. “About” when applied to numerical values indicates that the calculation or the measurement allows some slight imprecision in the value (with some approach to exactness in the value; approximately or

reasonably close to the value; nearly). If, for some reason, the imprecision provided by “about” and/or “substantially” is not otherwise understood in the art with this ordinary meaning, then “about” and/or “substantially” as used herein indicates at least variations that may arise from ordinary methods of measuring or using such parameters. In the present disclosure the terms “about” and “around” may allow for a degree of variability in a value or range, for example, within 10%, within 5%, or within 1% of a stated value or of a stated limit of a range. Likewise, in the present disclosure the term “substantially” can allow for a degree of variability in a value or range, for example, within 90%, within 95%, or within 99% of a stated value or of a stated limit of a range.

Although the open-ended term “comprising,” as a synonym of non-restrictive terms such as including, containing, or having, is used herein to describe and claim embodiments of the present technology, embodiments may alternatively be described using more limiting terms such as “consisting of” or “consisting essentially of” Thus, for any given embodiment reciting materials, components, or process steps, the present technology also specifically includes embodiments consisting of, or consisting essentially of, such materials, components, or process steps excluding additional materials, components or processes (for consisting of) and excluding additional materials, components or processes affecting the significant properties of the embodiment (for consisting essentially of), even though such additional materials, components or processes are not explicitly recited in this application. For example, recitation of a process reciting elements A, B and C specifically envisions embodiments consisting of, and consisting essentially of, A, B and C, excluding an element D that may be recited in the art, even though element D is not explicitly described as being excluded herein.

As referred to herein, disclosures of ranges are, unless specified otherwise, inclusive of endpoints and include all distinct values and further divided ranges within the entire range. Thus, for example, a range of “from A to B” or “from about A to about B” is inclusive of A and of B. Disclosure of values and ranges of values for specific parameters (such as amounts, weight percentages, etc.) are not exclusive of other values and ranges of values useful herein. It is envisioned that two or more specific exemplified values for a given parameter may define endpoints for a range of values that may be claimed for the parameter. For example, if Parameter X is exemplified herein to have value A and also exemplified to have value Z, it is envisioned that Parameter X may have a range of values from about A to about Z. Similarly, it is envisioned that disclosure of two or more ranges of values for a parameter (whether such ranges are nested, overlapping, or distinct) subsume all possible combination of ranges for the value that might be claimed using endpoints of the disclosed ranges. For example, if Parameter X is exemplified herein to have values in the range of 1-10, or 2-9, or 3-8, it is also envisioned that Parameter X may have other ranges of values including 1-9, 1-8, 1-3, 1-2, 2-10, 2-8, 2-3, 3-10, 3-9, and so on.

When an element or layer is referred to as being “on,” “engaged to,” “connected to,” or “coupled to” another element or layer, it may be directly on, engaged, connected, or coupled to the other element or layer, or intervening elements or layers may be present. In contrast, when an element is referred to as being “directly on,” “directly engaged to,” “directly connected to” or “directly coupled to” another element or layer, there may be no intervening elements or layers present. Other words used to describe the

relationship between elements should be interpreted in a like fashion (e.g., “between” versus “directly between,” “adjacent” versus “directly adjacent,” etc.). As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

Although the terms first, second, third, etc. may be used herein to describe various elements, components, regions, layers and/or sections, these elements, components, regions, layers and/or sections should not be limited by these terms. These terms may be only used to distinguish one element, component, region, layer or section from another region, layer, or section. Terms such as “first,” “second,” and other numerical terms when used herein do not imply a sequence or order unless clearly indicated by the context. Thus, a first element, component, region, layer, or section discussed below could be termed a second element, component, region, layer, or section without departing from the teachings of the example embodiments.

Spatially relative terms, such as “inner,” “outer,” “beneath,” “below,” “lower,” “above,” “upper,” and the like, may be used herein for ease of description to describe one element or feature’s relationship to another element(s) or feature(s) as illustrated in the figures. Spatially relative terms may be intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. For example, if the device in the figures is turned over, elements described as “below,” or “beneath” other elements or features would then be oriented “above” the other elements or features. Thus, the example term “below” can encompass both an orientation of above and below. The device may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein interpreted accordingly.

As used herein, the term “DI Water” refers to De-Ionized Water which is water that has been treated to remove all ions.

As used herein, the term “wt %” refers to weight percent which is the mass fraction of a substance within a mixture.

As used herein, the term “dosimeter” refers to a device that measures dose uptake of external ionizing radiation.

II. Description

As shown in FIGS. 2(a)-2(d), a sensor **100** includes a substrate **102**, an electrode **104**, **106**, and a conductive polymeric film **108**. More particularly, the sensor **100** may be a gamma radiation sensor. The substrate **102** may be a flexible substrate. The electrode **104**, **106** may be an interdigitated electrode. The interdigitated electrode **104**, **106** may include a first electrode **104** and a second electrode **106**. The first electrode **104** may include a plurality of first electrode digits **110**. The second electrode **106** may include a plurality of second electrode digits **112**. The interdigitated electrode **104**, **106** may be disposed on the substrate **102**. The conductive polymeric film **108** may include a blend **114**, **116** of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) **114** and polyvinyl alcohol (PVA) **116**. The blend **114**, **116** of PEDOT:PSS **114** and PVA **116** may be collectively known as a composite polymer and/or a PEDOT:PSS/PVA composite. The conductive polymeric film **108** may be disposed on the interdigitated electrode **104**, **106**. In a specific example, the conductive polymeric film **108** may be disposed on and between the first electrode **104** and the second electrode **106**. The sensor **100** may include an all-printed sensor that utilizes the blend **114**, **116** of PVA **114** and PEDOT:PSS **116** as an active radiation sensing material. The PEDOT:PSS **114** may act as the

electrically conductive medium, while the PVA **116** may advantageously provide ductility and stability of the printed sensor **100**. Upon radiation exposure, the PVA **116** may crosslink within a material matrix of the printed radiation sensor **100** militating against the recombination of chain scission by forming a semi-interpenetrating polymer network (SIPN) **118** with PEDOT:PSS **114** which may result in a more stable impedance reading. Desirably, the radiation sensor **100** may utilize scalable printing technologies which may further permit low-cost manufacturing of the radiation sensor **100** at large scale.

The use of PVA **116** provides many advantages over other stabilizing agents in known radiation sensors. For instance, PVA **116** is water soluble and may provide desirable cross-linking properties. In a specific example, as shown in FIGS. **1(a-b)**, PVA **116** may crosslink when exposed to gamma radiation which may then be configured to hold PEDOT:PSS chains **114** in place after scission. Without being bound to any particular theory, it is believed that holding the PEDOT:PSS chains **114** in place may result in a linear change in resistance as opposed to an exponential increase. Desirably, the linear change in resistance enhances the stability of the impedance reading for sensing purposes. One skilled in the art may utilize other sensing materials to accommodate various ranges of radiation doses, within the scope of the present disclosure.

The use of PEDOT:PSS **114** provides many advantages over other electrically conductive mediums in known sensors. For instance, PEDOT:PSS **114** may be provided as a more efficient and cost-sensitive way to manufacture the radiation sensor **100** due to its current use as a printed material. Additive manufacturing and printing technologies involve building a part or product by gradually adding layers of material to create a final product. Advantageously, additive manufacturing may reduce the amount of material needed to produce products compared to traditional subtractive manufacturing in which parts are machined. Further, additive manufacturing allows for quick production of finely detailed parts. In certain circumstances, the radiation sensor **100** may be a printed and a disposable sensor developed through additive manufacturing and configured for single use applications. By developing the radiation sensor **100** as a printed dosimeter, the radiation sensor **100** may be manufactured more efficiently and provided less expensively when compared to known sensors. Desirably, the radiation sensor **100** provided as a printed material may also be more easily incorporated into packaging designs. In a specific example, the sensor **100** may be disposed on, within, and/or coupled to a packaged product. In a more specific example, the sensor **100** may be disposed on, within, and/or coupled to a packaged medical device.

The blend **114, 116** of the conductive polymeric film **108** may include various amounts of PEDOT:PSS **114** and PVA **116**. In a specific example, the blend **114, 116** may include about 5-50 wt % of polyvinyl alcohol (PVA) **116**, and about 50-95 wt % of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) **114**. In a more specific example, the blend **114, 116** may include about 7.5-12.5% of polyvinyl alcohol (PVA) **116**, and about 87.5-92.5 wt % of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) **114**. In an even more specific example, the blend **114, 116** may include about 10 wt % of polyvinyl alcohol (PVA) **116**, and about 90 wt % of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) **114**.

In certain circumstances, the radiation sensor **100** may include ways of enhancing the adhesion and the spreading of

the blend **114, 116** onto the interdigitated electrode **104, 106**. For instance, the sensor **100** may be plasma treated to provide a desirably decreased contact angle CA. More specifically, the interdigitated electrode **104, 106** may be plasma treated. Advantageously, the decreased contact angle CA may increase the surface wettability of the composite polymer, thereby making it easier to consistently cover the complete electrode **104, 106** interdigitated area with the blend **114, 116**. Further, the increased wettability of the plasma treated interdigitated electrode **104, 106** may also desirably enhance the adhesion of the blend **114, 116** to the surface of the interdigitated electrode **104, 106**.

In another embodiment, the present technology includes methods of using the sensor **100**. For instance, a method **200** of using the sensor **100** may include a step **202** providing a sample to be treated by radiation. In a specific example, the radiation may be gamma-radiation. The method **200** may also include a step **204** of providing a sensor **100** having a substrate **102**, an electrode **104, 106**, and a conductive polymeric film **108**. The substrate **102** may be flexible. The electrode **104, 106** may be an interdigitated electrode including a first electrode **104** with a plurality of first electrode digits **110** and a second electrode **106** with a plurality of second electrode digits **112**. The interdigitated electrode **104, 106** may be disposed on the substrate **102**. The conductive polymeric film **108** may include a blend **114, 116** of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) **114** and polyvinyl alcohol (PVA) **116**. The conductive polymeric film **108** may be disposed on the interdigitated electrode **104, 106**. In a specific example, the conductive polymeric film **108** may be disposed on and between the first electrode **104** and the second electrode **106**. In certain circumstances, the method **200** may also include a step **206** of plasma-treating the sensor **100**. More particularly, the interdigitated electrode **104, 106** of the radiation sensor **100** may be plasma-treated. In a specific example, the step of plasma-treating the sensor **100** may be performed as the sensor **100** is manufactured and/or before the step **204** of providing the sensor **100**. Next, the method **200** may include a step **208** of disposing the sensor **100** within a predetermined proximity to the sample. The predetermined proximity may include disposing the sensor **100** substantially adjacent to the sample, disposing the sensor **100** within the same packaging as the sample, and/or disposing the sensor **100** substantially adjacent to the packaging containing the sample. Afterwards, gamma radiation may be applied to the sample. The method **200** may further include monitoring a dose range of the gamma radiation applied to the sample with the sensor **100**. In certain circumstances, the sensor **100** may be configured to provide a substantially linear relative change in resistance with a gamma radiation dose range of greater than zero kilogray to about fifty-three kilogray.

III. Example

Provided as a specific, non-limiting example, one embodiment of the radiation sensor **100** was produced by providing an aqueous dispersion of 1.3 wt. % PEDOT:PSS (0.5 wt. % PEDOT content and 0.8 wt. % PSS content,) as well as PVA powder (Mw 9,000-10,000, 80% hydrolyzed), which were obtained from SIGMA ALDRICH®. The PEDOT:PSS and PVA powder may be used without any further purification. For PEDOT:PSS/PVA composite preparation, a PVA stock solution was made by dissolving 10 wt. % PVA in de-ionized water and stirring at 90° C. for two hours followed by thirty minutes in an oven at 70° C. for thirty minutes. The PEDOT:PSS suspension was filtered with 12 µm pore-size

filter paper. The filtered PEDOT:PSS suspension and the PVA solution were mixed to obtain PEDOT:PSS-PVA composites **114**, **116** with 10 wt. %, 25 wt. % and 50 wt. % solid content of PVA **116**. Each composite mixture **114**, **116** was stirred for at least 24 hours before casting.

As shown in FIGS. **2(a)**-**2(d)**, provided as a non-limiting example and according to one embodiment of the present disclosure, the printed radiation sensor **100** was manufactured employing scalable technologies for printing electronics. More specifically, the interdigitated electrodes **104**, **106** were printed with an MPS™ TF-100 screen printer and dried at one-hundred twenty degrees Celsius for five minutes, as shown in FIG. **2(b)**. Screen-printed electrodes **104**, **106** were constructed from DUPONT® 5025 silver paste with a sheet resistivity of 12-15 mΩ/sq/mil onto polyethylene terephthalate (PET) sheets due to their enhanced bendability and thermal stability. To improve adhesion and spreading of the blend **114**, **116**, the screen-printed electrodes **104**, **106** were plasma treated using a PE-25 plasma etching system for forty-five seconds operated at 50 kHz frequency and 200 W power, as shown in FIG. **2(c)**. Immediately after plasma treatment, around 50 μL of each blend **114**, **116** was cast onto the interdigitated area of the electrodes **104**, **106** and dried at lab conditions (293±2 K and 40% RH), as shown in FIG. **2(d)**. Sensor impedance was monitored after casting, and the sensors **100** were not used until they reached stability after several days after casting. As a result, a batch of fourteen printed sensors **100** per PET sheet were produced employing this efficient process. It should be appreciated that the printed radiation sensor **100** may be configured to be manufactured by roll-to-roll manufacturing systems.

The effect of plasma treatment on surface wettability was investigated by the sessile drop technique on a contact angle Ramé-Hart® Model 290 F1 Advanced Goniometer. Contact angle CA measurements were performed depositing drops of 10 μL volume of each solution on both plasma-treated and pristine PET substrates. The contact angles CA were measured from a left side and a right side of the drop, and average readings were recorded. Each contact angle CA measurement was repeated five times on new surfaces. All measurements were then averaged to give an averaged contact angle CA and their corresponding standard deviation.

The adhesion between PEDOT:PSS/PVA films **108** and the printed electrodes **104**, **106** was evaluated in accordance with the American Society for Testing and Materials (ASTM D3330) by attaching a strip of pressure-sensitive tape fully covering the films **108** cast on top of the printed electrodes **104**, **106**. The attached tape strip was continuously and firmly peeled away at around a 90° angle to the films **108**. The peeling test was conducted in triplicates for each composite cast in both pristine electrodes **104**, **106** and plasma-treated electrodes **104**, **106**.

Three dosimeters per PEDOT:PSS/PVA composite **114**, **116** were dried in lab conditions (293±2 K and 40% RH) for 24 days. Impedance measurements were carried out using an LCR meter (LCR-821, GW Instek) at 1 kHz frequency and 0.1 V amplitude voltage. The electrical impedance was reported as a percentage of relative impedance change using the following equation:

$$\frac{\Delta Z}{Z_0} (\%) = \left(\frac{Z - Z_0}{Z_0} \right) * 100\%$$

Where $\Delta Z/Z_0$ is the relative impedance change expressed in a percentage, and Z_0 is the initial impedance measurement after casting. The initial impedance of each PEDOT:PSS/PVA composite **114**, **116** was calculated as the arithmetical average of all samples.

For each experiment, three printed dosimeters **100** per PEDOT:PSS/PVA composition **114**, **116** were irradiated in the range of 0 kGy to 53 kGy using a gamma radiation source. More specifically, the gamma radiation source used was Gamma Cell 220 ® from Atomic Energy of Canada with a cobalt-60 source. The upper dose limit was set to around 50 kGy, given that this radiation dose has been previously used for the sterilization of human bone and tendon allograft. The absorbed dose of the printed sensors **100** was calculated based on the radiation exposure time and the decay corrected dose rate provided by the manufacturer set at 2.3 kGy/day. Impedance measurements were collected and reported in relative impedance change in the following intermediate absorbed doses: 0 kGy, 4.9 kGy, 9.5 kGy, 16 kGy, 21.2 kGy, 32.2 kGy, 39.03 kGy, 48.44 kGy and 53.39 kGy. After reaching a 53 kGy dose, dosimeter impedance was monitored for the subsequent eighteen days using the same LCR meter and reported in terms of relative impedance change every three days.

To study the effects of gamma radiation on the chemical structure of the composite polymeric films **108**, non-irradiated and irradiated samples were examined by Attenuated Total Reflection Fourier Transform Infrared Spectroscopy (ATR-FTIR) using a PerkinElmer® Spectrum **100** FTIR Spectrometer over the range of 3800 cm⁻¹ to 650 cm⁻¹. Thermogravimetric analysis (TGA) was performed with a Netzsch® TG 203 F3 Tarsus, heating the non-irradiated and irradiated samples to 700° C. at a 20° C./min.

To verify the in-situ crosslinking of PVA **116** and the subsequent formation of a SIPN **118** after radiation exposure, changes in solubility were assessed by submerging the composites in glass containers with 3.5 mL of DI water for one-hundred hours under gentle agitation (400 rpm). The amount of PEDOT:PSS dissolved in the DI water was determined by ultraviolet-visible spectroscopy (UV-Vis spectroscopy). It should be appreciated that UV-Vis spectroscopy may be configured to analyze a sample at 1000 nm wavenumber. A linear calibration curve per each composite **114**, **116** was created measuring the produced absorbance of the following dissolution percentages: 20%, 40%, 60%, 80% and 100%.

FIGS. **3(a)**-**(b)** show the contact angle CA measurements performed on pristine and plasma-treated PET substrates **102**. As shown in FIG. **3(a)**, there was a substantial decrease in contact angle CA on all plasma-treated substrates **102** compared to non-plasma-treated PET substrates **102**. This significant difference in contact angle CA is observable in all measurements irrespective of the PEDOT:PSS/PVA composite **114**, **116** deposited. In a specific example, the conductive polymeric film **108** of the plasma treated samples may have a contact angle CA that is less than sixty degrees. With reference to FIG. **3(b)**, the average contact of all pristine PET substrate **102** is around 75° and the plasma treated samples exhibited a contact angle CA less than 42°. Similar results were observed previously between water drops deposited pristine and plasma treated PET substrate **102**. This increase in surface wettability of plasma treated samples is attributed to the introduction of chemical functional groups that interacts with the PEDOT:PSS/PVA composites **114**, **116**. Moreover, with continued reference to FIG. **3(b)**, the addition of PVA **116** also resulted in a decrease of contact angle CA measurements. Without being bound to

any particular theory, it is believed this occurred due to the interaction of alcohol groups on the PVA chains **116** with polar groups on the PET surface. Advantageously, as a result of the increased surface wettability, it may be easier to consistently cover the complete electrode **104**, **106** interdigitated area with the composite materials **114**, **116**. In contrast, as shown in FIG. **4**, spreading of the composites **114**, **116** onto the electrode **104**, **106** interdigitated area of the not plasma-treated sensors **100** was difficult and, in some cases, left uncovered regions between digits. With continued reference to FIG. **4**, the increased wettability of plasma treated surfaces desirably also led to better adhesion of the composite materials to the surface of the electrodes **104**, **106**.

To investigate the impedance stability of printed sensors **100** after casting, periodic readings every three days were carried out for the subsequent twenty-four days of air exposure at room temperature. As shown in FIG. **5(b)**, after casting, the initial impedance values for pure PEDOT:PSS **120** and PEDOT:PSS/PVA composites with 10 wt % PVA **122**, 25 wt % PVA **124**, and 50 wt % PVA **126** content were 1.28 k Ω , 1.73 k Ω , 2.75 k Ω and 4.48 k Ω , respectively. The sensor impedance consistently increased with PVA **116** weight percent since the PEDOT:PSS (conductive material within the composite) content **114** was decreased. As shown in FIG. **5(a)**, the evolution of sensor impedance is measured as a function of time (air exposure). While pure PEDOT:PSS sensors experienced a slight impedance increase, the PEDOT:PSS-PVA composites **122**, **124**, **126** exhibited a significant impedance decrease proportional to the PVA **116** content, especially during the first week after casting. Without being bound to any particular theory, it is believed the noticeable decrease in impedance is due to the slow desorption of free water from the PEDOT:PSS/PVA composites **122**, **124**, **126** over time. After twenty-four days, the relative impedance changes of pure PEDOT:PSS **120** and PEDOT:PSS/PVA **122**, **124**, **126** composites were 7%, -3%, -17% and -23%, respectively.

As shown in FIG. **6(a)**, the conductivity dependence on the radiation dose of PEDOT:PSS/PVA composites **114**, **116**. In terms of sensitivity to radiation, pristine PEDOT:PSS was the most sensitive tested material reaching relative average impedance changes in the order of 3,000% at 53 kGy. However, the dispersion of sensor readings also increased with radiation dose, showing undesirably large variations after passing 40 kGy (not plotted). For instance, at 53 kGy dose, pure PEDOT:PSS sensors exhibited impedance changes between 1970% and 6900%. On the other hand, PVA **116** reduced the sensor sensitivity but at the same time, the dispersion of readings was reduced. This is the case of composites with 10 wt % PVA **122** whose impedance gradually increased until reaching 49% change at 40 kGy with a standard deviation of $\pm 6.9\%$. Similarly, composites with 25 wt % PVA **124** increased their impedance by about $25\% \pm 5.0\%$. This increment on impedance is associated to the disruption of electrical pathways in PEDOT polymer chains due to chain scission upon radiation. FIG. **6(b)** shows the long-term stability of the printed sensors **100** after receiving 53 kGy of radiation exposure. Pure PEDOT:PSS manifested the largest variations in impedance over the eighteen-day time frame, which may be attributed to the recombination effect of free radicals present in the film **108**. At day seven after radiation, pure PEDOT:PSS experienced an average impedance change of twenty-three percent while in day eighteen presented negative twenty-three percent of impedance change. Unlike the pure PEDOT:PSS sensors, those with even 10 wt % PVA **122** remained relatively stable

in the same timeframe. For instance, the sensor **100** with the blend **114**, **116** including PEDOT:PSS **114** and PVA **116** may have an average impedance change within fifteen percent over an eighteen-day period after radiation exposure. This improvement in stability may be ascribed to the formation of the in situ semi-interpenetrating polymer network **118** between PEDOT:PSS **114** and PVA **116** polymer chains reducing polymer chain recombination. One skilled in the art may use other methods to form the semi-interpenetrating polymer network **118** of the sensor **100**, within the scope of the present disclosure.

FIGS. **7(a-d)** display the FTIR spectra of the printed sensors **100** at different radiation exposures. FIG. **7(a)** shows the full range FTIR spectra for pure PEDOT:PSS samples **120**. FIG. **7(b)** shows an enlarged spectra of the fingerprint region appearing within the wavenumber range of 1700 cm⁻¹ to 650 cm⁻¹. The peaks at 1524 cm⁻¹ and 1271 cm⁻¹ are assigned to C=C and C—C stretching vibrations of the thiophene ring in PEDOT polymer chains respectively. The observed peaks at 946 cm⁻¹, 862 cm⁻¹, and 676 cm⁻¹ correspond to stretching of C—S bond in the thiophene ring of PEDOT chains. Additionally, peaks at 1181 cm⁻¹, 1120 cm⁻¹, and 1057 cm⁻¹ can be assigned to the C—O—C bond stretching which originates in the ethylenedioxy group of PEDOT chains. PSS functional groups are confirmed by the peaks at 1038 cm⁻¹ and 1010 cm⁻¹ which correspond to the stretching of a sulfonic acid group (SO₃—) and the observed peak at 1632 cm⁻¹ related to the stretching of less strained C=C bonds originating in the benzene rings found in PSS polymer chains. FIG. **7(b)** represents a noticeable decrease in the intensity of several peaks by increasing the radiation exposure. Specifically, the peaks at 1524 cm⁻¹, 1271 cm⁻¹, and 862 cm⁻¹ that are assigned to the C=C, C—C, C—S, respectively in PEDOT chains exhibited a significant decrease in intensity. Similarly, the observed peak at 1632 cm⁻¹, 1038 cm⁻¹, and 1010 cm⁻¹ which corresponded to the C=C and the stretching of sulfonic acid group in PSS chains decreased by radiation exposure time. The observed reduction in peak intensities represents that the polymer degradation of PEDOT:PSS originated from the exposure to the high levels of radiation.

FIG. **7(c)** and FIG. **7(d)** display the FTIR spectra of PEDOT:PSS/PVA composites with 50 wt % PVA **126**. As shown in FIG. **7(c)**, a broad absorption band at around 3396 cm⁻¹, associated to the symmetrical stretching vibration of the —OH groups, was observed. Further, the peaks appearing at 2924 cm⁻¹ and 2854 cm⁻¹ can be attributed to the C—H stretching vibration of PVA and PSS chains. Similar to the FTIR of irradiated pure PEDOT:PSS samples, a decrease in all peak intensities associated with PEDOT and PSS was observed, as shown in FIG. **7(c)**. However, the decrease of —OH functional groups in the PVA trials can be attributed to the crosslinking among PVA chains **116**, giving rise to the formation of a SIPN **118** with gamma radiation.

FIG. **9(a-d)** illustrates the thermogravimetric analysis of composites (TGA) curves of the irradiated and the non-irradiated dosimeters. As shown in FIG. **9(a)**, the pure PEDOT:PSS samples **120** are shown to have three mass loss regions. The first mass loss region observed from sixty degrees Celsius to one-hundred fifty degrees Celsius may be attributed to the evaporation of water. The second mass loss, from one-hundred fifty degrees Celsius to three-hundred degrees Celsius, can be attributed to the PSS decomposition through a rupture of the sulfonate group from styrene. Finally, the third mass loss region from three-hundred degrees Celsius to six-hundred degrees Celsius can be ascribed to the rupture of the PEDOT/PSS polymer back-

bone. TGA curves of pure PEDOT:PSS **120** revealed that the irradiated samples degraded at a slightly faster rate and retained about forty percent weight at six-hundred degrees Celsius which is 1.5% less than non-irradiated samples. This subtle difference in degradation rate and mass loss can be attributed to the polymer degradation observed in the FTIR spectra of irradiated pure PEDOT:PSS samples **120**. In contrast, as shown in FIGS. **9(b-d)** irradiated PEDOT:PSS/PVA composites **122, 124, 126** retained more mass compared to non-irradiated composites with the same PVA content **122, 124, 126**. Thus, composites with 10 wt % **122**, 25 wt % **124**, and 50 wt % **126** PVA content retained 1.82%, 5.46%, and 4.53% more weight, respectively. Advantageously, this enhancement in thermal stability can be attributed to the crosslinked PVA structure formed upon radiation, which is in accordance with the FTIR results.

To confirm crosslinking of PVA **116** and the formation of a SIPN **118** after radiation exposure, the water solubility of both irradiated and non-irradiated films **108** was examined. It is well known that both PEDOT:PSS **114** and PVA **116** are water-soluble polymers. Even though PEDOT is not water-soluble by itself, the small PEDOT polymer chains are tightly bonded to the long PSS polymer chains **114**, which in turn, are water-soluble making the whole material water-soluble. However, the crosslinked forms of PSS **114** and PVA **116** are not water soluble and can be produced by ionizing radiation exposure under certain processing conditions. FIG. **8** illustrates the non-irradiated and the irradiated samples soaked in DI water at room temperature subjected to gentle agitation at four-hundred revolutions per minute (RPM). All non-irradiated films, irrespectively of their composition, started to dissolve as soon as they were soaked in the de-ionized water, changing the aqueous media color to a characteristic light blue color of PEDOT:PSS. As shown in FIG. **8**, this visual outcome, alongside the FITR results, confirms that non-irradiated films have no crosslinked structures and are water soluble. A similar behavior was shown in irradiated pure PEDOT:PSS films **120**, which are fully soluble in DI water. Since irradiated PEDOT:PSS films did not exhibit any change in solubility, the crosslinking degree of PSS polymer chains was null or very small after irradiation. In contrast, irradiated films **108** containing 10 wt % PVA **122**, 25 wt % PVA **124**, and 50 wt % PVA **126** became insoluble after radiation exposure indicating crosslinking of PVA polymer chains **116**. Further, the appearance of a lighter circular area for the irradiated samples, as shown in FIG. **8**, represents that the polymer degradation was indeed responsible for the observed conductivity. Advantageously, as shown in FIG. **10**, even after one-hundred hours of submersion in DI water, the irradiated films **108** containing 10 wt % PVA **122**, 25 wt % PVA **124**, and 50 wt % PVA **126** remained attached to the substrate **102** exhibiting outstanding film integrity without apparent PEDOT:PSS **114** leaching supported by the lack of color change in the aqueous media.

As shown in FIGS. **11(a)-(d)**, the amount of PEDOT:PSS **114** dissolved in DI water was quantitatively analyzed by UV-Vis Spectroscopy. As shown in FIGS. **11(a-d)**, all non-irradiated films showed one-hundred percent dissolution in the first ten minutes of the dissolution test. However, no trials of PEDOT:PSS **114** leaching was detected in any of the irradiated films **108** containing PVA **116** in their composition. Accordingly, even the addition of 10 wt % of PVA **116** was enough to form a SIPN **118** upon irradiation, thus reducing the polymer recombination and enhancing stability of readings after radiation exposure.

Advantageously, the sensor **100** enhances the certainty of adequate sterility and may be manufactured more efficiently over known radiation sensors. The sensor **100** also enhances the adhesion and the spreading of the composite polymer **114, 116** onto the interdigitated electrode **104, 106** by plasma-treating the sensor **100**.

Example embodiments are provided so that this disclosure will be thorough and will fully convey the scope to those who are skilled in the art. Numerous specific details are set forth such as examples of specific components, devices, and methods, to provide a thorough understanding of embodiments of the present disclosure. It will be apparent to those skilled in the art that specific details need not be employed, that example embodiments may be embodied in many different forms, and that neither should be construed to limit the scope of the disclosure. In some example embodiments, well-known processes, well-known device structures, and well-known technologies are not described in detail. Equivalent changes, modifications and variations of some embodiments, materials, compositions, and methods can be made within the scope of the present technology, with substantially similar results.

What is claimed is:

1. A sensor, wherein the sensor comprises:

a substrate;

an interdigitated electrode disposed on the substrate; and
a conductive polymeric film comprising a blend of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) and polyvinyl alcohol (PVA), wherein the conductive polymeric film is disposed the interdigitated electrode.

2. The sensor of claim 1, wherein the substrate is a flexible substrate.

3. The sensor of claim 1, wherein the interdigitated electrode includes first electrode with a plurality of first electrode digits and a second electrode with a plurality of second electrode digits.

4. The sensor of claim 1, wherein the blend includes about 5-50 wt % of polyvinyl alcohol (PVA), and about 50-95 wt % of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS).

5. The sensor of claim 4, wherein the blend includes about 7.5-12.5 wt % of polyvinyl alcohol (PVA), and about 87.5-92.5 wt % of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS).

6. The sensor of claim 5, wherein the blend includes about 10 wt % of polyvinyl alcohol (PVA), and about 90 wt % of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS).

7. The sensor of claim 1, wherein the sensor is plasma treated.

8. The sensor of claim 1, wherein the conductive polymeric film has a contact angle that is less than sixty degrees.

9. The sensor of claim 1, wherein the sensor is substantially insoluble after radiation exposure.

10. The sensor of claim 1, wherein the conductive polymeric film is disposed on and between the plurality of digits of the first electrode and the plurality of digits of the second electrode.

11. The sensor of claim 1, wherein the sensor is a gamma radiation sensor.

12. The sensor of claim 1, wherein the sensor is a printed and a disposable sensor.

13. The sensor of claim 1, wherein the sensor is configured to form a semi-interpenetrating polymer network.

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14. The sensor of claim 1, wherein the sensor has an average impedance change within fifteen percent over an eighteen-day period after radiation exposure.

15. A packaged product comprising a sensor according to claim 1.

16. A packaged medical device comprising a sensor according to claim 1.

17. A method of measuring gamma radiation dose comprising:

- providing a sample to be treated with radiation;
- providing a sensor including:
 - a substrate;
 - an interdigitated electrode comprising a first electrode with a plurality of digits and a second electrode with a plurality of digits, wherein the interdigitated electrode is disposed on the substrate; and
 - a conductive polymeric film comprising a blend of poly(3,4-ethylenedioxythiophene) polystyrene

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sulfonate (PEDOT:PSS) and polyvinyl alcohol (PVA), wherein the film is disposed on and between said first and second electrodes of said interdigitated electrode;

5 disposing the sensor within a predetermined proximity to the sample;

applying radiation to the sample; and

monitoring a dose range of the radiation applied to the sample with the sensor.

10 18. The method of claim 17, wherein the radiation is gamma radiation.

19. The method of claim 17, wherein the sensor is configured to provide a substantially linear relative change in resistance with a gamma radiation dose range of greater than zero kilogray to about fifty-three kilogray.

15 20. The method of claim 17, further comprising a step of plasma-treating the sensor.

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