

(12) **United States Patent**  
**Miranda et al.**

(10) **Patent No.:** **US 9,016,108 B1**  
(45) **Date of Patent:** **Apr. 28, 2015**

(54) **GRAPHENE BASED REVERSIBLE  
NANO-SWITCH/SENSOR SCHOTTKY DIODE  
(NANOSSSD) DEVICE**

(75) Inventors: **Felix A Miranda**, Olmsted Falls, OH (US); **Onoufrios Theofylaktos**, Avon Lake, OH (US); **Nicholas J Pinto**, Caguas, PR (US); **Carl H Mueller**, Strongsville, OH (US); **Javier Santos**, North Ridgeville, OH (US); **Michael A Meador**, Strongsville, OH (US)

(73) Assignee: **The United States of America as Represented by the Administrator of National Aeronautics and Space Administration**, Washington, DC (US)

(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 618 days.

(21) Appl. No.: **13/242,300**

(22) Filed: **Sep. 23, 2011**

(51) **Int. Cl.**  
**G01N 7/00** (2006.01)  
**H01L 29/16** (2006.01)

(52) **U.S. Cl.**  
CPC ..... **H01L 29/1606** (2013.01)

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

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,617,824 A \* 11/1971 Shinoda et al. .... 257/407  
3,767,984 A \* 10/1973 Shinoda et al. .... 257/268

|                   |         |                       |             |
|-------------------|---------|-----------------------|-------------|
| 7,719,318 B1      | 5/2010  | Nordquist et al. .... | 326/104     |
| 7,785,557 B2      | 8/2010  | Gruner et al. ....    | 423/445 R   |
| 7,944,728 B2      | 5/2011  | Nian et al. ....      | 365/148     |
| 8,421,131 B2 *    | 4/2013  | Chung et al. ....     | 257/288     |
| 2009/0174435 A1   | 7/2009  | Stan et al. ....      | 326/112     |
| 2009/0235721 A1   | 9/2009  | Robinson et al. ....  | 73/31.05    |
| 2009/0294759 A1   | 12/2009 | Woo et al. ....       | 257/29      |
| 2010/0021708 A1   | 1/2010  | Kong et al. ....      | 423/220     |
| 2010/0025660 A1   | 2/2010  | Jain et al. ....      | 257/24      |
| 2010/0055464 A1   | 3/2010  | Sung ....             | 428/408     |
| 2010/0140723 A1   | 6/2010  | Kurtz et al. ....     | 257/415     |
| 2010/0213435 A1   | 8/2010  | Fujii et al. ....     | 257/9       |
| 2010/0218801 A1   | 9/2010  | Sung et al. ....      | 136/244     |
| 2010/0255964 A1   | 10/2010 | Wang ....             | 502/185     |
| 2010/0327847 A1   | 12/2010 | Leiber et al. ....    | 324/71.1    |
| 2011/0048625 A1   | 3/2011  | Caldwell et al. ....  | 156/233     |
| 2011/0059599 A1   | 3/2011  | Ward et al. ....      | 438/507     |
| 2011/0068290 A1   | 3/2011  | Haddon et al. ....    | 252/62.51 R |
| 2011/0068320 A1   | 3/2011  | Marinero et al. ....  | 257/9       |
| 2011/0089404 A1   | 4/2011  | Marcus et al. ....    | 257/29      |
| 2011/0102068 A1   | 5/2011  | Bouchiat et al. ....  | 327/527     |
| 2013/0040397 A1 * | 2/2013  | Star et al. ....      | 436/121     |
| 2014/0103296 A1 * | 4/2014  | Yu et al. ....        | 257/29      |

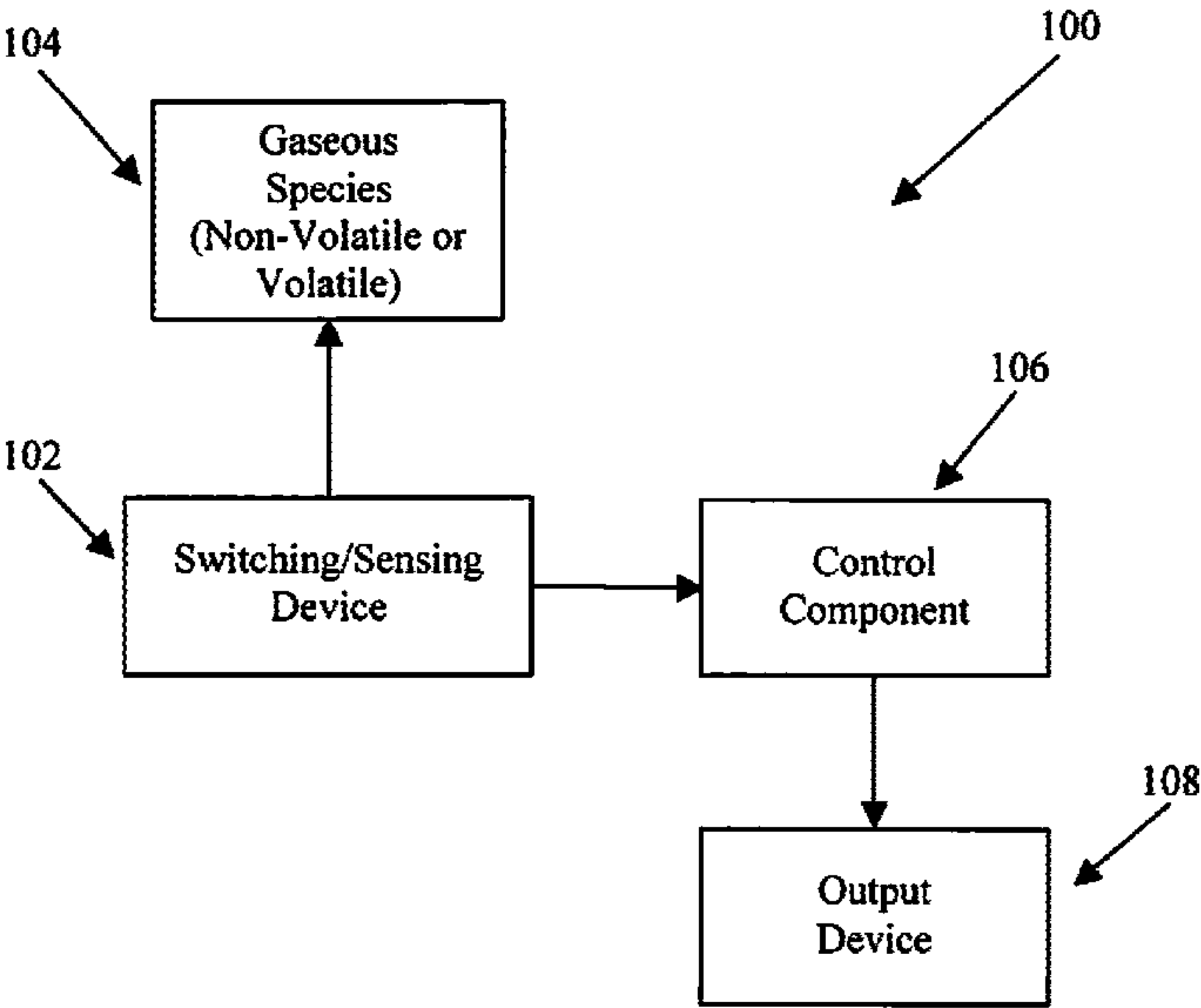
\* cited by examiner

Primary Examiner — Andre Allen  
(74) Attorney, Agent, or Firm — Robert H. Earp, III

(57) **ABSTRACT**

A nanostructure device is provided and performs dual functions as a nano-switching/sensing device. The nanostructure device includes a doped semiconducting substrate, an insulating layer disposed on the doped semiconducting substrate, an electrode formed on the insulating layer, and at least one layer of graphene formed on the electrode. The at least one layer of graphene provides an electrical connection between the electrode and the substrate and is the electroactive element in the device.

**20 Claims, 6 Drawing Sheets**





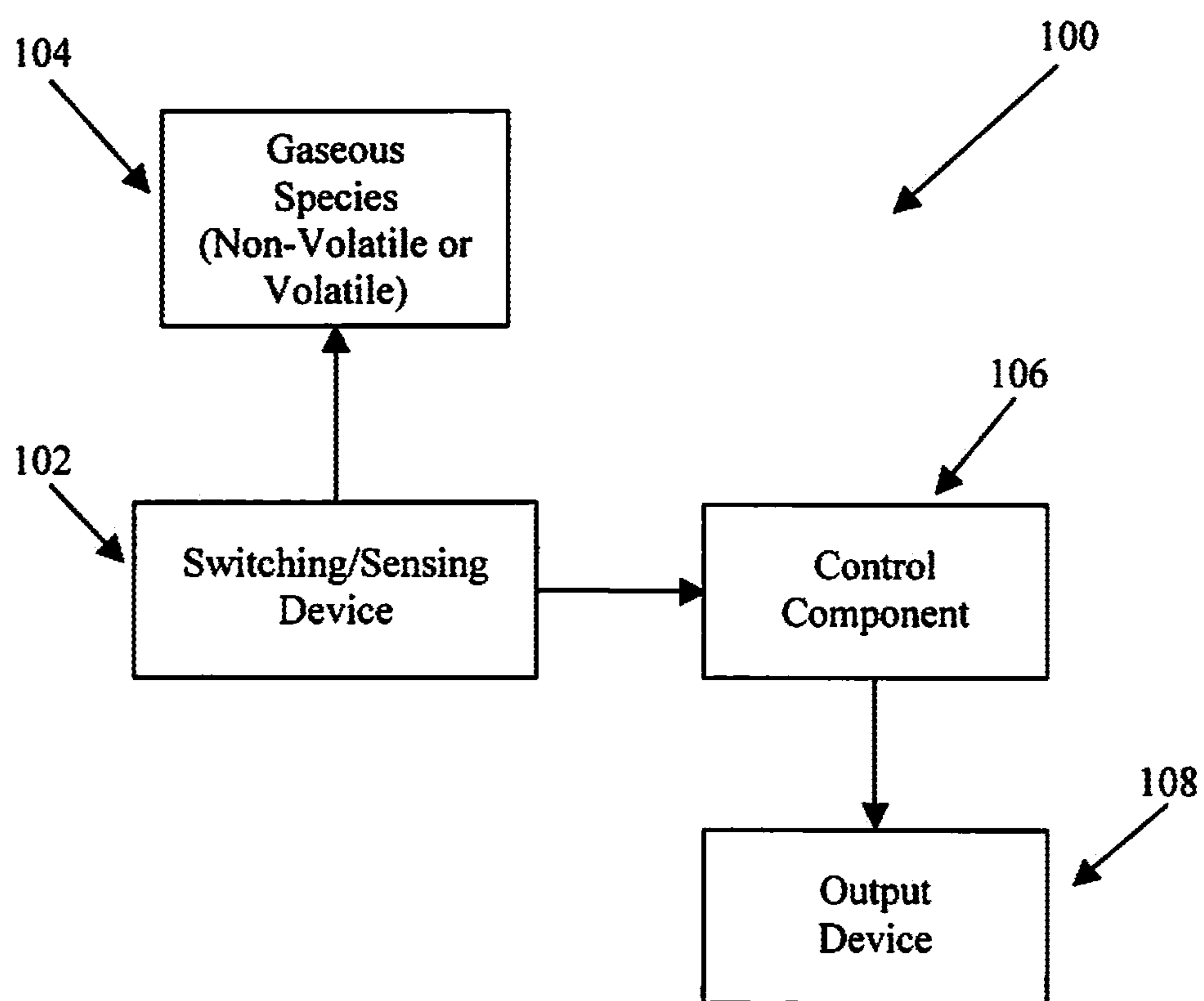


FIG. 1



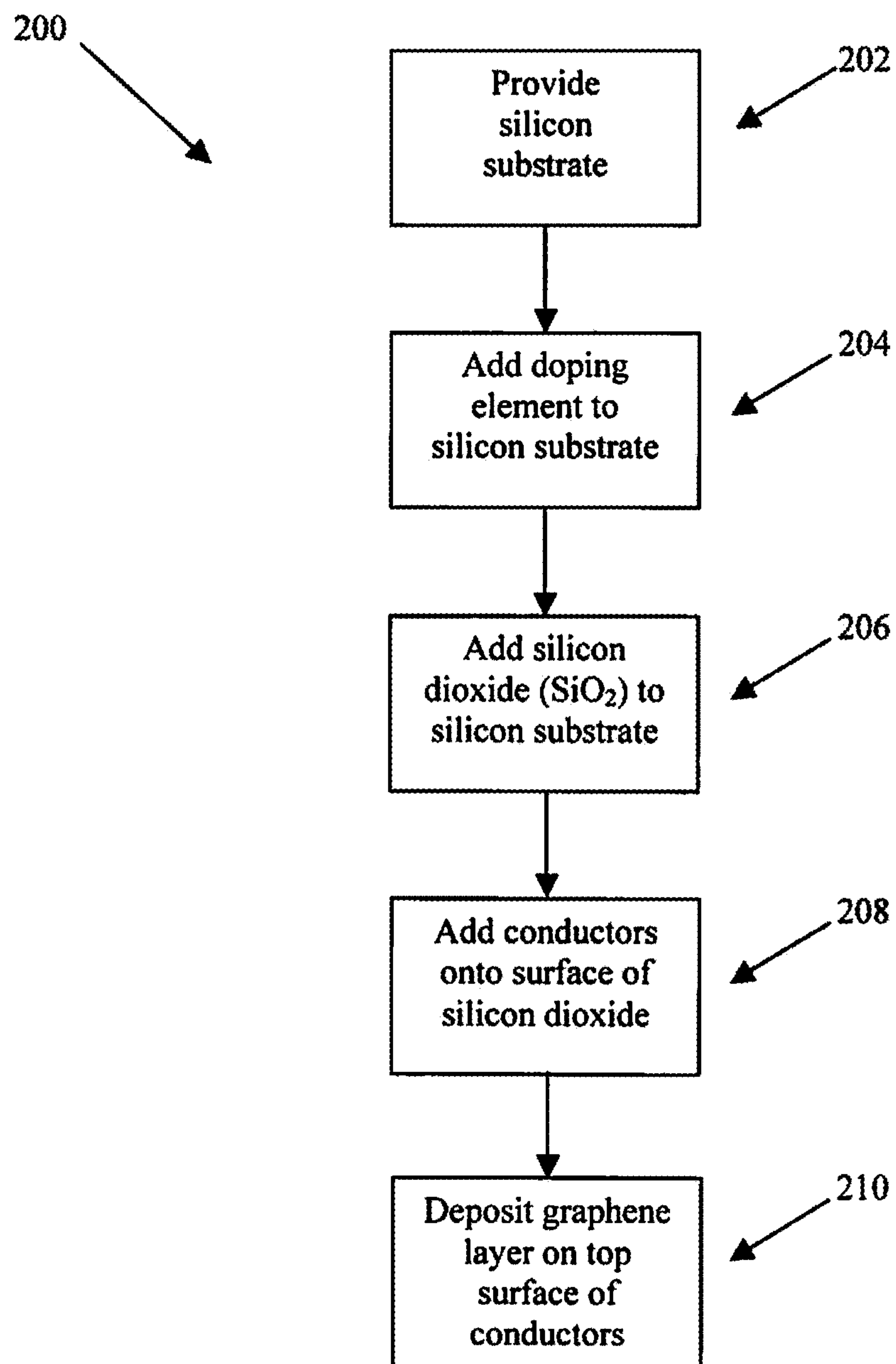


FIG. 2



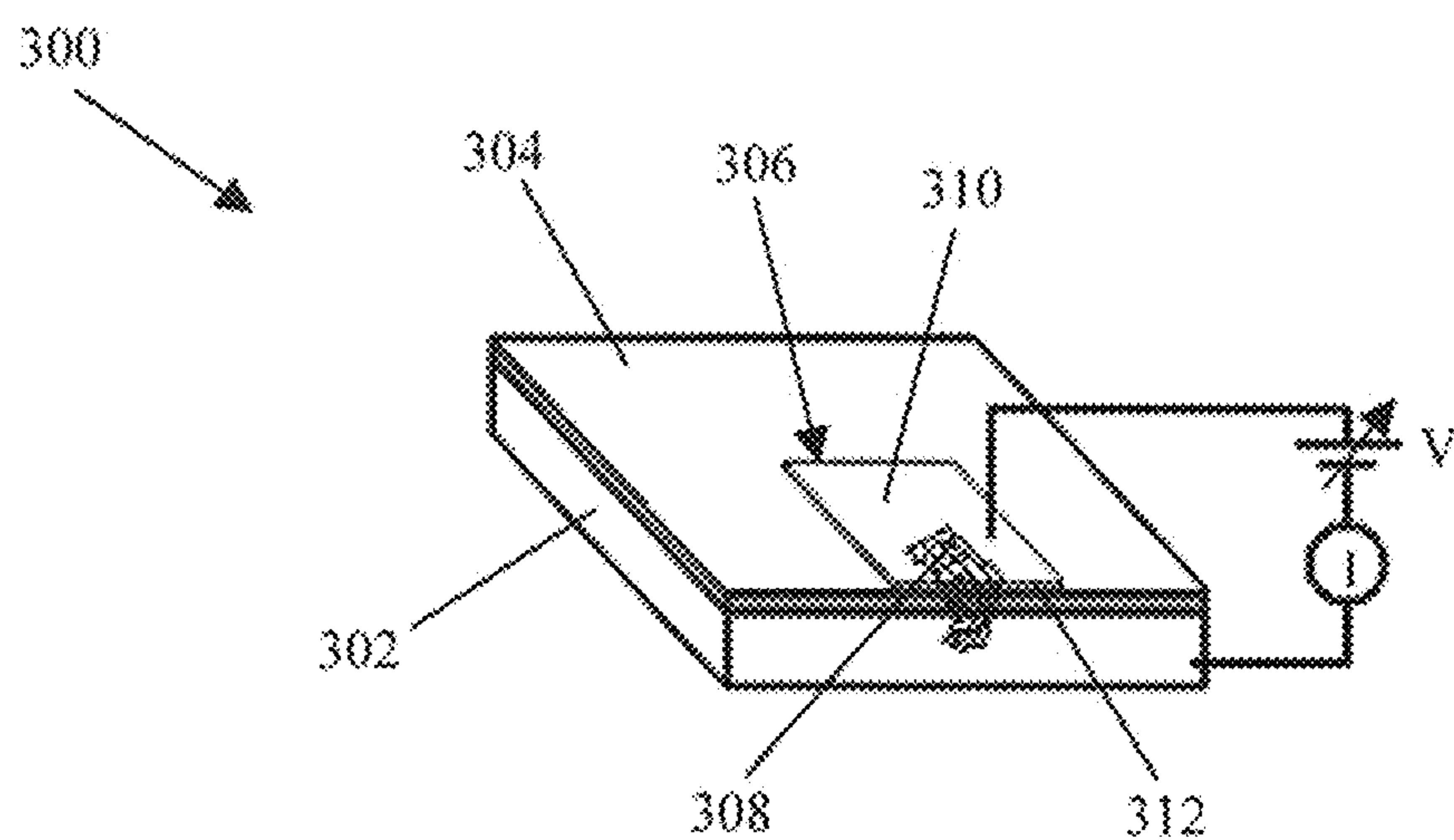


FIG. 3(A)

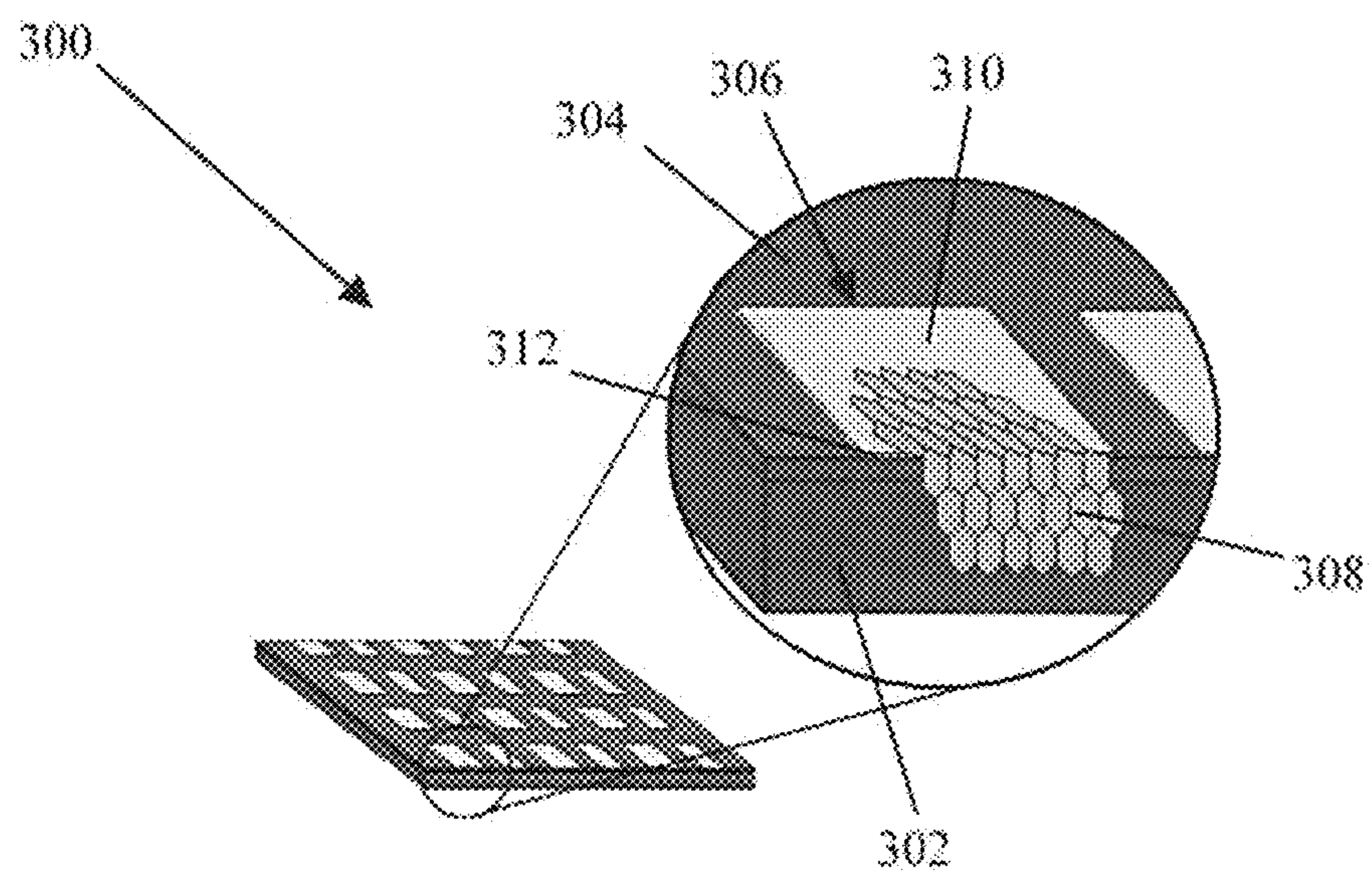


FIG. 3(B)



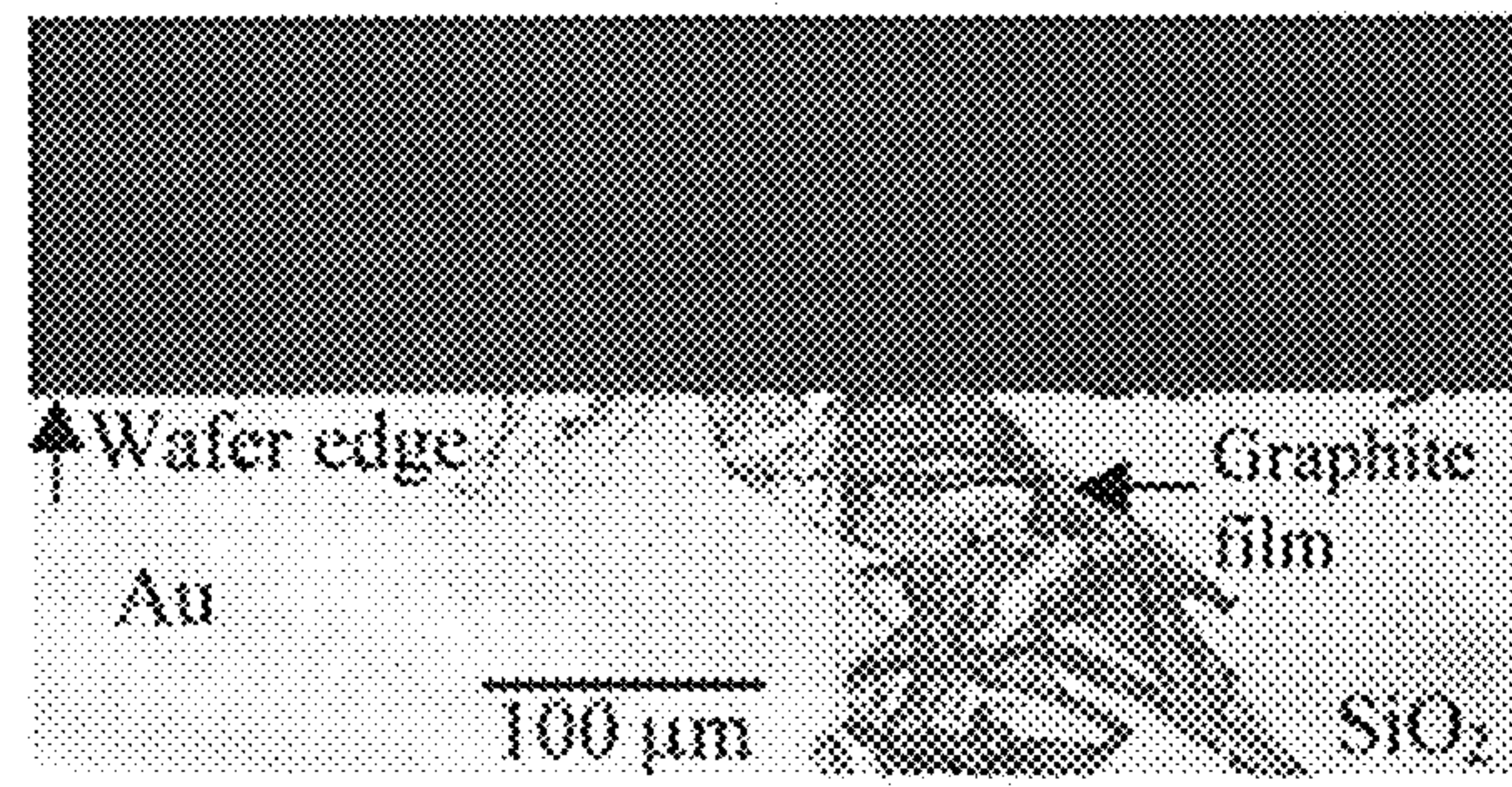


FIG. 4

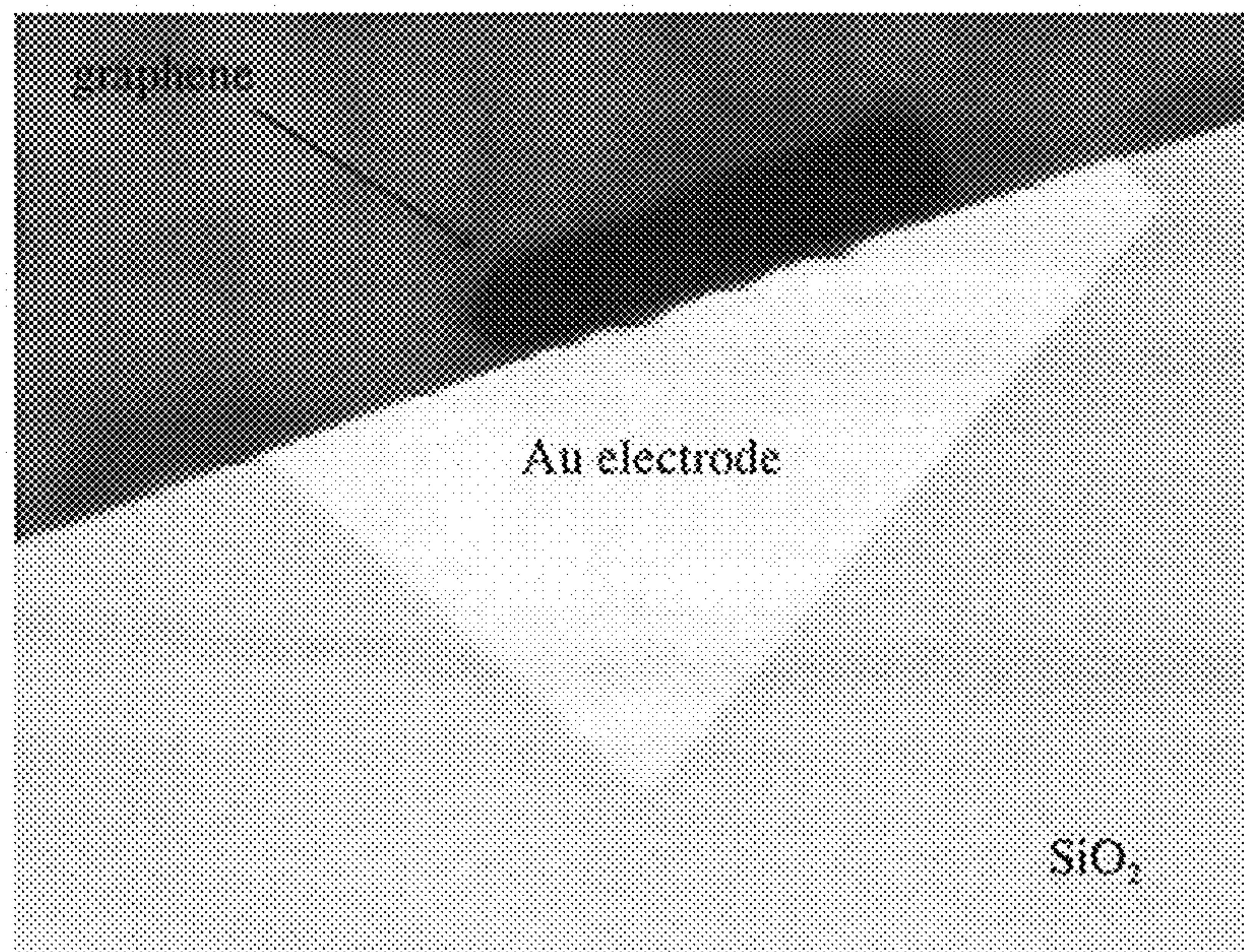


FIG. 5



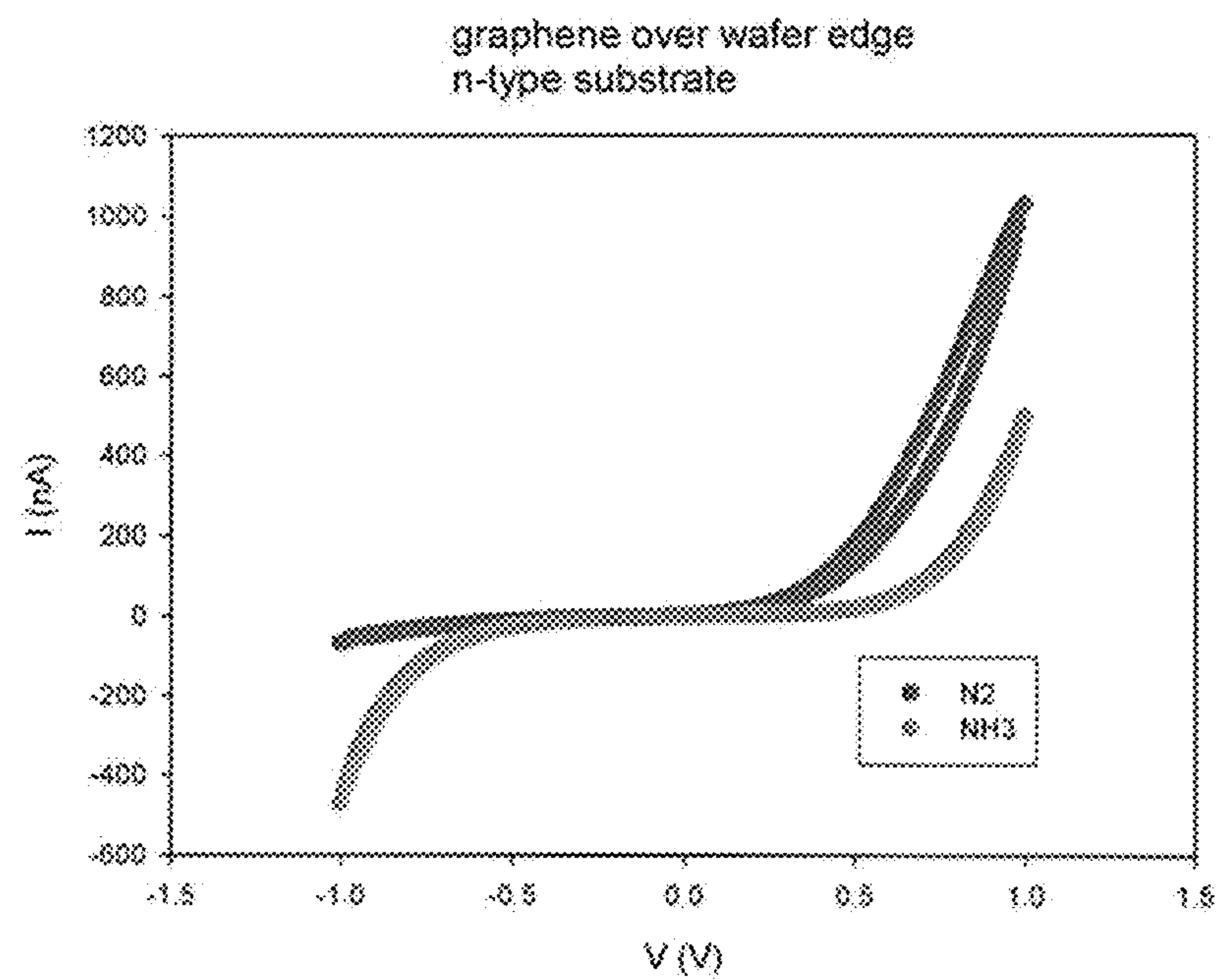


FIG. 6

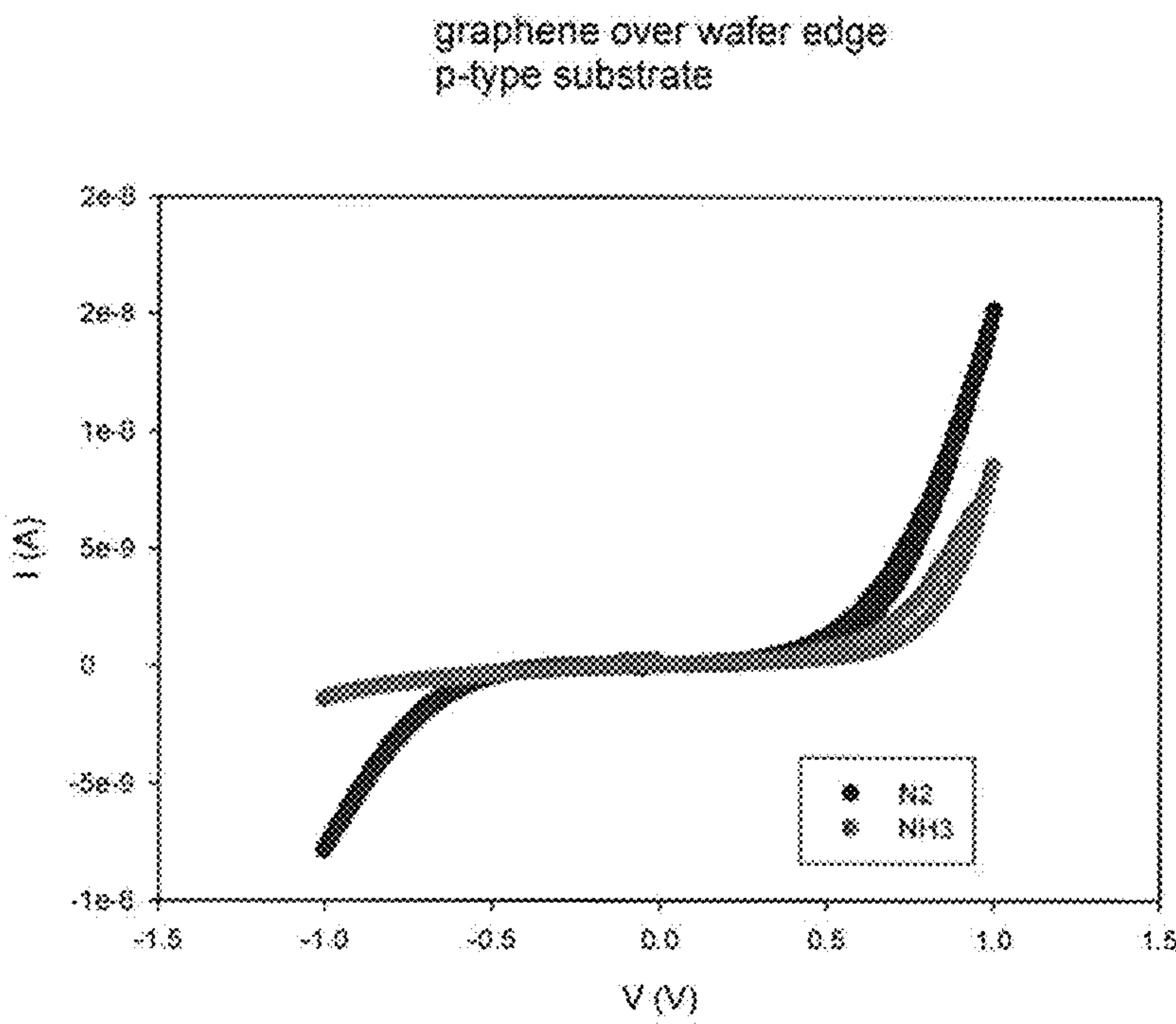


FIG. 7



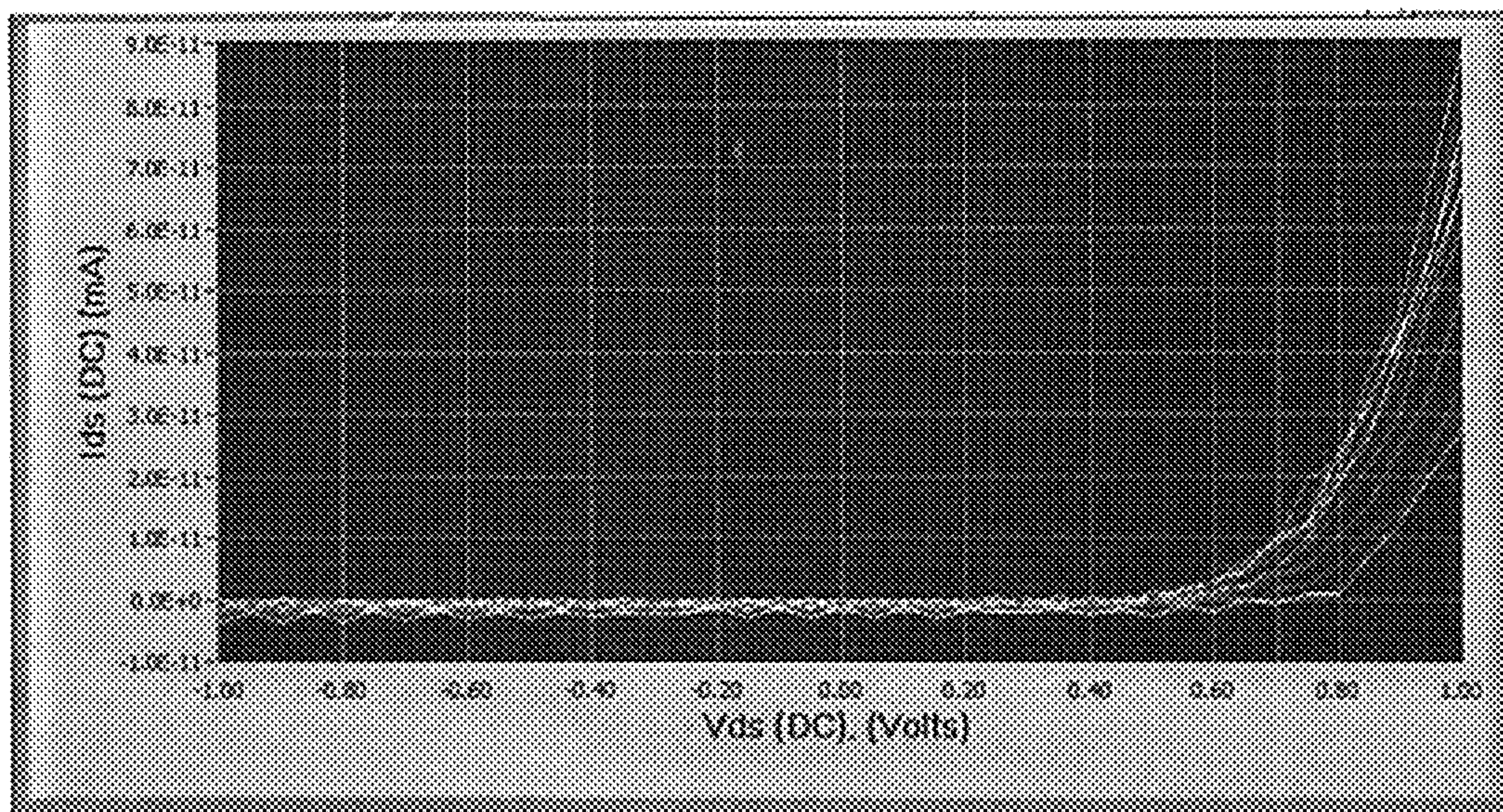


FIG. 8

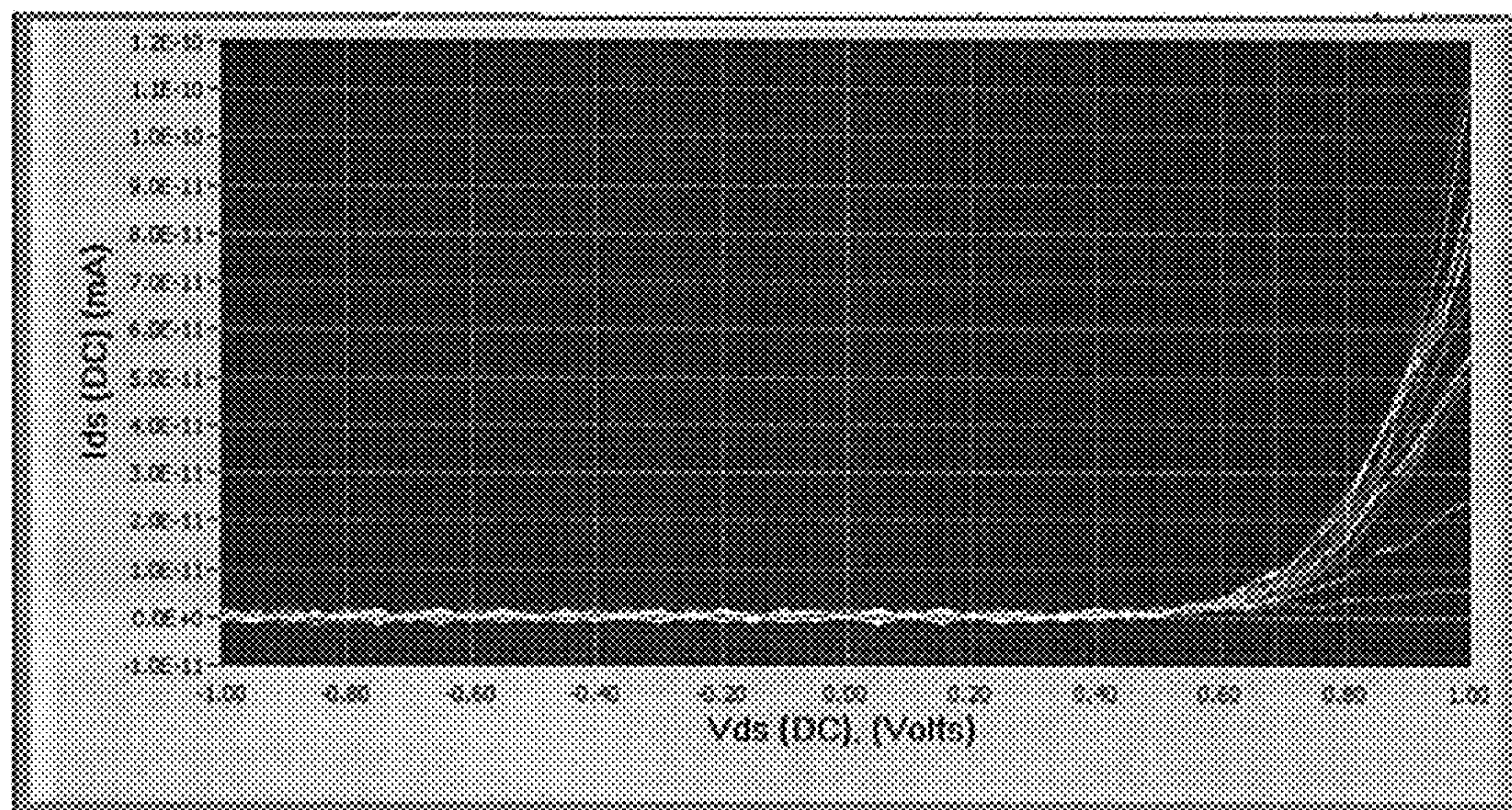


FIG. 9



## 1

**GRAPHENE BASED REVERSIBLE  
NANO-SWITCH/SENSOR SCHOTTKY DIODE  
(NANOSSSD) DEVICE**

ORIGIN OF THE INVENTION

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

BACKGROUND

Developing technologies in support of monitoring the health of astronauts and the operation of critical instrumentation are ongoing in order to develop a better understanding of the changes in the human body and equipment anticipated in future space exploration. Accordingly, the emergence of promising technologies such as nanotechnology has sparked efforts to develop operational electronic and sensing devices at the nanoscale level with performance and sensing resolutions not yet achieved. These efforts have resulted in great specificity attained by tailoring the surface of sensors (i.e., surface modification) by optical, chemical and physical means (i.e., via the creation of preferred end-groups using approaches such as self-assembled monolayers).

One key or unique issue with these approaches is that sensing takes place via the attachment of molecules of the desired species to the sensor end groups bringing it into an irreversible saturated state via physical adsorption or chemical adsorption. More importantly, in most instances, the nature of the sensor is such that its mean-time-before-failure (MTBF) is limited (e.g., sensors that are cantilever-based or any other rendition that contains moving parts). This poses a reliability concern especially when working with embedded sensors such as BioMEMS sensors, or sensors intended for remote, difficult to access locations such as spacecraft or robotic probes for planetary exploration.

Traditional approaches for developing state-of-the-art sensing technologies targeted for specific applications are costly, mostly due to the expensive laboratory and facilities infrastructure required for their fabrication and high-volume production. In addition, the hybrid integrated approach of the different circuit components makes size reduction difficult. Reduced size is a relevant requirement in applications such as Bio-embedded devices. Traditionally, even those sensing devices developed at the nanostructure level perform only a unifunctional, specific sensing task and not a dual switching/sensing function. Switching enables the device to autonomously respond to changes in normal conditions and trigger appropriate responses, and then revert to baseline operation once the environment being sensed has returned to normal.

For this dual functionality, the current state of the art on nano-switch/sensors are based on metal oxide components (e.g., ZnO) with circuits consisting of mechanical actuators such as cantilevers, which include many non-trivial fabrication steps. Furthermore, the mechanical nature of these conventional sensors limits reliability due to a reduction on the MTBF. This level of complexity may be a critical disadvantage that can hinder the transition of the device from laboratory demonstration to practical working applications.

SUMMARY

The following presents a simplified summary in order to provide a basic understanding of some aspects of the innova-

## 2

tion. This summary is not an extensive overview of the innovation. It is not intended to identify key/critical elements or to delineate the scope of the innovation. Its sole purpose is to present some concepts of the innovation in a simplified form as a prelude to the more detailed description that is presented later.

The innovation disclosed and claimed herein, in one aspect thereof, comprises a nanostructure device adapted to perform dual functions as a nano-switching/sensing device. The device includes a doped substrate, an insulating layer disposed on the substrate (e.g. silicon substrate), an electrode formed on the insulating layer, and at least one layer of graphene formed on the electrode. At least one layer of graphene provides an electrical connection between the electrode and the substrate and is the electroactive element in the device.

In another aspect of the innovation, the nanostructure device is based on a use of graphene to develop a diode at the nanoscale level.

In yet another aspect of the innovation, based on experimental performance of the nanostructure device, the innovation exhibits dual use functionality (e.g., switching and sensing) and reversibility characteristics.

In still another aspect of the innovation, the nanostructure device can be fabricated using either n-doped or p-doped silicon substrate, which adds another dimension for applications of the device by enhancing its compatibility with other silicon-based nanoelectronic circuits.

In yet another aspect, the innovation has no moving parts, which is contrary to conventional nanosensors that rely on cantilevers and other mechanical/moving parts. As a result, the innovation offers reliable performance with a long mean-time-before-failure (MTBF).

To accomplish the foregoing and related ends, certain illustrative aspects of the innovation are described herein in connection with the following description and the annexed drawings. These aspects are indicative, however, of but a few of the various ways in which the principles of the innovation can be employed and the subject innovation is intended to include all such aspects and their equivalents. Other advantages and novel features of the innovation will become apparent from the following detailed description of the innovation when considered in conjunction with the drawings.

In addition, there is no reported work on a graphene-based dual use nano-switch/sensor device for toxic gases. Consequently, the innovation reported in this disclosure represents the first proof of concept of that possibility.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates an example system incorporating a dual function nanostructure device in accordance with the innovation.

FIG. 2 illustrates an example fabrication process of the dual function nanostructure device in accordance with the innovation.

FIG. 3A illustrates an example schematic of dual function nanostructure device in accordance with the innovation.

FIG. 3B illustrates an example schematic of a pre-patterned doped substrate in accordance with aspects of the innovation.

FIG. 4 illustrates an example microscopic image of a graphene film crossing a wafer edge in accordance with the innovation.

FIG. 5 illustrates an example micrograph illustrating contact of graphene with an electrode in accordance with aspects of the innovation.



FIG. 6 illustrates an example experimental response of the dual function nanostructure device in accordance with the innovation.

FIG. 7 illustrates an example experimental response of the dual function nanostructure device in accordance with the innovation.

FIG. 8 illustrates an example I-V (Current-Voltage) characteristic of the dual function nanostructure device with the introduction of the volatile species in accordance with the innovation.

FIG. 9 illustrates an example I-V characteristic of the dual function nanostructure device with the removal of the volatile species in accordance with the innovation.

#### DETAILED DESCRIPTION

The innovation is now described with reference to the drawings, wherein like reference numerals are used to refer to like elements throughout. In the following description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the subject innovation. It may be evident, however, that the innovation can be practiced without these specific details.

While specific characteristics are described herein (e.g., thickness), it is to be understood that the features, functions and benefits of the innovation can employ characteristics that vary from those described herein. These alternatives are to be included within the scope of the innovation and claims appended hereto.

Further, in view of the aspects and features described, methodologies that may be implemented in accordance with embodiments of the subject innovation will be better appreciated with reference to the figures. While for purposes of simplicity of explanation, the methodologies are shown and described as a series of drawings representing steps or acts associated with the methodologies, it is to be understood and appreciated that the claimed subject matter is not limited by the order of the drawings, as some drawings may occur concurrently with other drawings and/or in different orders than what is depicted and described herein. Where non-sequential, or branched, flow is illustrated via flowchart, it can be appreciated that various other branches, flow paths, and orders of the blocks, may be implemented which achieve the same or a similar result. Moreover, not all illustrated drawings may be required to implement the methodologies described herein-after.

The innovation described herein and shown in the figures, in one aspect thereof, is representative of a nanostructure that may be a dual use nano-switching/sensing device comprised of a graphene-based nano-Schottky diode. The performance of the innovation has been experimentally tested in an ambient atmosphere as well as under other non-volatile and volatile atmospheres. For example, the innovation has been experimentally tested under ammonia gas ( $\text{NH}_3$ ), but could operate under other volatile or toxic gases, such as hydrogen, hydrocarbons, nitrogen oxides, carbon monoxide, carbon dioxide, etc. The resulting experimental data disclosed herein, demonstrates a dual switching/sensing nature (and function) of the innovation. Hence, the acronym nanoSSSD (nano-Switch/Sensor Schottky Diode). Further, the resulting experimental data also reveals a reversible characteristic of the innovation, which makes it suitable for nanosensing applications where access to the sensor and its potential replacement opportunities are limited (e.g., biosensors, harsh environment, etc.).

Specifically, due to the following characteristics of graphene, the innovation has extreme sensitivity to different

gaseous species with a remarkable attribute of having reversibility properties, thereby serving as a building block for a volatile species sensor. As is known, graphene is formed from a single layer (one atom thick) of carbon and has a hexagonal shape. Thus, graphene is a 2-dimensional material and, as such, its entire volume is exposed to its surroundings, thereby making it sensitive to the adsorption and desorption of a single gas molecule. Further, graphene's single layer structure makes graphene a zero-gap semiconductor, where the valence band and the conduction band overlap, thereby giving graphene superior electrical conduction and low electrical noise properties. This high electrical conductance also contributes to graphene's sensitivity to the adsorption and desorption of a single gas molecule. Because graphene is sensitive to the adsorption and desorption of gas molecules, the resistivity of graphene also changes, thereby giving the graphene-based innovation its sensing ability. Therefore, the innovation, when operating as a sensor, is able to cycle between active and passive sensing states in response to the presence or absence, respectively, of the gaseous species. Furthermore, graphite is a three-dimensional material that is derived from stacking multiple layers of graphene. The electrical properties of thin layers of graphite will more closely resemble the electrical properties of graphene than those of thick graphite layers. The advantages of using graphite for the present invention include ease of fabrication and compatibility with standard semiconductor device processing techniques. Hence, the current device uses graphite as the sensing element as well as graphene.

In addition, because of the aforementioned sensitivity and diode properties, the device can be used as a switch whose operational stages (i.e., open/close or on/off) could be controlled by a given gaseous species. Consequently, the innovation has great potential as a building block for implementation of a switch/sensor device for harsh, embedded or enclosed environments (e.g., human body, space-based habitats, aircraft, rail, etc.) where the longevity and reusability of the circuit are critical for reliable operation. Furthermore, graphene's excellent electrical and physical properties such as the ability to maintain current densities approximately a million times higher than that of copper, record strength of 200 times greater than steel, and elastic stretching capabilities of up to 20%, will make this device more robust than those made from nano-cantilevers comprised of more fragile metal oxides.

With reference now to the figures, FIG. 1 illustrates an example system **100** implementing the innovation. The system **100** may be a system where the exposure of a volatile or toxic gas may be harmful to humans and/or critical equipment. Some example systems may include airports and mass transportation systems, airplanes, and space platforms that require emissions monitoring, leak detection, engine monitoring, security, fire detection, personal health monitoring, environmental monitoring, etc. The system **100** includes a dual function nano-switching/sensing device **102**, a gaseous species **104** introduced to the nano-switching/sensing device **102**, a control component **106**, and an output device **108**.

The nano-switching/sensing device **102** is a graphene-based nano-Switch/Sensor Schottky Diode (nanoSSSD) and will be described in more detail further below in reference to FIGS. 2, 3(A), and 3(B). The control component **106** receives information from the nano-switching/sensing device **102** and outputs a signal to the output device **108**. For example, if the nano-switching/sensing device **102** senses a gaseous species **104**, the switching portion of the nano-switching/sensing device **102** can automatically actuate thereby sending a signal



## 5

to the control component 106. The control component 106 in turn can activate the output device 108, which may be in the form of a warning device.

With reference to FIGS. 2, 3A, and 3B simultaneously, FIG. 2 illustrates a process 200 to fabricate a nanostructure device 300, shown schematically in FIG. 3A, incorporating the nano-switching/sensing device 102. At step 202, a wafer is provided in the form of a single crystal, such as silicon (Si), to form a substrate 302. At step 204, a doping agent or dopant is added to the substrate 302. The doping agent may be either an n-type (donor) or a p-type (acceptor) dopant. It should be noted that the responsiveness of the nanostructure device 300 differs depending on the substrate doping type. At step 206, an insulator 304 is formed on the substrate 302. In an example embodiment, the substrate is an n-type or a p-type doped silicon (Si) substrate and the insulator 304 is a thermally grown layer of silicon dioxide (SiO<sub>2</sub>). In the example embodiment, the silicon resistivity of the doped silicon substrate 302 is on the order of 1-10 ohms per centimeter. Further, the thickness of the SiO<sub>2</sub> insulating layer 304 has a thickness of approximately 100-300 nm. However, the nanoSSSD is only modestly impacted by oxide thickness and can operate over a wider range of oxide thickness than listed above. Fabrication of the nanostructure device 300 utilizing a silicon-based substrate enhances its compatibility with other silicon-based nanostructures.

At step 208, a pattern of electrodes 306 are formed on the substrate 302 using microfabrication techniques (e.g., sputter deposition, etc.). In an example embodiment shown in FIGS. 4-5, the electrodes 306 are gold (Au) electrodes and are disposed on the substrate 302 in a square checker-board type pattern. In other example embodiments, however, the electrodes 306 may be formed on the substrate 302 in any type of pattern (e.g., circular, rectangular, etc.).

Graphene 308 is deposited on a top surface 310 of each electrode 306 and extends over an edge 312 of the electrode 306 so as to contact the substrate 302, illustrated in FIGS. 3A and 3B. The graphene 308 provides a conductive path between the electrode 306 and the substrate 302, thus forming the nanostructure device 300 and more specifically, a Schottky diode. The graphene 308 may include a single layer of graphene or multiple layers of graphene. Further, the graphene 308 may be produced by microfabrication techniques (e.g., exfoliation methods, chemical vapor deposition, etc.).

In another example embodiment, the graphene 308 is formed on the top surface 310 of at least two electrodes 306 and a semiconducting region, which includes a portion of the substrate 302 and the insulator 304, between the at least two electrodes 306. As mentioned above, graphene 308 is sensitive to the adsorption and desorption of a single gas molecule. In an example embodiment, the semiconducting region, which includes the substrate 302 and/or the insulator 304, may be etched such that the gaseous species to be sensed has direct physical access to both a top and bottom surface of the graphene 308.

FIGS. 4 and 5 represent micro-images of the nanostructure 300. Specifically, FIG. 4 is a top optical view microscopic image magnified 200 times of an actual graphene layer crossing the edge of the substrate 302. FIG. 5 is a micrograph that illustrates the contact of the graphene layer 308 with the electrode 306, which is disposed on the SiO<sub>2</sub> insulating layer 304.

Referring again to FIG. 3A, a dc voltage may be applied between the electrode 306 and the substrate 302 to thereby activate of the nanostructure device 300. The resulting I-V (Current-Voltage) characteristics of the nanostructure device

## 6

300 are illustrated in FIGS. 7-10. As illustrated, when the nanostructure device 300 is exposed to a volatile species (e.g., ammonia (NH<sub>3</sub>)), the response (diode response) is unambiguously different to that manifested under normal ambient conditions.

Specifically, FIG. 6 shows the experimental I-V characteristic response of the nanostructure device 300 for the n-type doped silicon substrate 302 when the atmosphere is changed from a non-volatile species (e.g., nitrogen (N<sub>2</sub>)) to a volatile species (NH<sub>3</sub>). Similarly, FIG. 8 illustrates the experimental I-V characteristic response of the nanostructure 300 for the p-type doped silicon substrate 302 when the atmosphere is changed from the non-volatile species (N<sub>2</sub>) to the volatile species (NH<sub>3</sub>).

As described above, FIGS. 6 and 7 illustrate how the nanostructure device 300 responds when the nanostructure device 300 is exposed to a volatile species. Also significant, however, is the behavior of the nanostructure device 300 (shown in FIGS. 8 and 9) when the volatile species is removed. Specifically, as illustrated in FIGS. 8 and 9, the performance of the nanostructure device 300 returns to its normal mode of operation as the volatile species is removed.

Referring to FIG. 8, illustrated are I-V characteristics of the nanostructure device 300 when the volatile gaseous species NH<sub>3</sub> is introduced into an ambient atmosphere. As the volatile species NH<sub>3</sub> is introduced, the I-V curve shifts to the left. Specifically, prior the introduction of the NH<sub>3</sub>, the I-V curve is represented by the purple line. As the NH<sub>3</sub> is introduced the I-V curve gradually shifts to the left and is represented by the yellow line.

Conversely, referring to FIG. 9, illustrated are I-V characteristics of the nanostructure device 300 with the removal of the volatile gaseous species NH<sub>3</sub> and the atmosphere returns to the ambient atmosphere. As the volatile species NH<sub>3</sub> is removed, the I-V curve shifts to the right. Specifically, prior to the removal of the NH<sub>3</sub>, the I-V curve is represented by the dark blue line. As the NH<sub>3</sub> is introduced the I-V curve gradually shifts to the right and is represented by the light blue line.

As clearly illustrated by FIGS. 8 and 9 and as indicated above, the performance of the nanostructure device 300 returns to its normal mode of operation as the volatile species is removed. This reversible feature forms the basis for the functional operation of the nanostructure device 300, thus, resulting in a reliable, long mean-time-before-failure (MTBF) nano-switch/sensor that is ideal for applications where frequent replacement of the nanostructure device 300 is not a viable option. In addition, based on the same feature, the nanostructure device 300 could act as a switch whose performance could be tailored by dispensing or retrieving the particulates of the volatile species.

While, as discussed above, there are other alternate approaches for attaining nanosensors, the innovation discussed here is unique not only because of the use of graphene, but also because of the fully reversible (i.e., reusable) dual nature of the nanostructure device 300 (i.e., nano-switch/sensor). As a result, the innovation presented in this disclosure has many unique and novel features. First, the nanostructure device 300 is based on a use of graphene to develop such a diode at the nanoscale. Second, because of the properties of graphene (i.e., maximization of sensing surface due to 2-dimensional nature, robustness, good electrical conductivity, etc.) the nanostructure device 300 is extremely reliable, e.g., even under a harsh environment (i.e., human body internal environment; extreme cold/hot temperature environments; etc.). Third, contrary to conventional nanosensors, which rely on cantilevers and other mechanical/moving parts, the innovation has no moving parts and, as such, promises to offer



reliable performance with a long MTBF. Fourth, based on the performance of the device, the innovation exhibits dual use functionality. Specifically, the device can function as a sensor and a switch. Fifth, the device can be fabricated using either n-doped or p-doped silicon, which adds another dimension for applications of the device by enhancing its compatibility with other silicon-based nanoelectronic circuits. Sixth, the innovation is based on a vertical configuration, which saves highly coveted circuit area, but may also be based on other configurations. Seventh, the fabrication procedure is economical and therefore offers the possibility of low cost implementation when compared to traditional approaches.

The aforementioned functionalities can be either exploited separately or in tandem depending on the specific application, which adds to the versatility of the device. Specifically, the innovation described herein has many potential commercial applications beyond those of traditional devices. For example, research groups have attempted to demonstrate a graphene-based switch with potential for applications in the non-volatile memory market. The device, however, functions only as a switch. In other words, unlike the innovation described herein, the conventional device does not exhibit sensing functions. Further, others have demonstrated, what they claim to be, the world's fastest graphene transistor operational at 26 GHz. This non-silicon based device, however, is not capable of both sensing and switching applications.

The innovation described herein, on the other hand, has the potential to expand the applications of combined switching/sensing graphene based nanoelectronics not only in areas ranging from embedded biomedical devices but also to extremely sensitive detection/switching devices required for earth or space-bound applications on harsh environment (e.g., airplanes turbines; surveillance of airports and mass transportation systems such as subways and trains; space platforms such as the International Space Station (ISS), Crew Exploration Vehicles (CEV), lunar and planetary habitats, etc.).

Specific potential applications of the innovation include the detection of toxic gases such as ammonia, hydrogen, hydrocarbons, nitrogen oxides ( $\text{NO}_x$ ) (i.e., NO and  $\text{NO}_2$ ), carbon monoxide (CO), and carbon dioxide  $\text{CO}_2$ .

In addition, this device can be used to detect explosives, e.g., in an effort to prevent terrorist attacks. For example, the device can detect 2,4-dinitrotoluene, which is a volatile material found in TNT explosives.

In yet other aspects, the innovation can be connected to a visual and sound alarm that will be autonomously triggered in the presence of gas and return to its passive mode in absent of it. Further, the device can respond differently to each gas and, therefore, may be possible to generate colored signals, for example, where colors correspond to a specific detected gas.

What has been described above includes examples of the innovation. It is, of course, not possible to describe every conceivable combination of components or methodologies for purposes of describing the subject innovation, but one of ordinary skill in the art may recognize that many further combinations and permutations of the innovation are possible. Accordingly, the innovation is intended to embrace all such alterations, modifications and variations that fall within the spirit and scope of the appended claims. Furthermore, to the extent that the term "includes" is used in either the detailed description or the claims, such term is intended to be inclusive in a manner similar to the term "comprising" as "comprising" is interpreted when employed as a transitional word in a claim.

What is claimed is:

1. A nanostructure device comprising:  
a doped semiconducting substrate;  
an insulating layer disposed on the doped semiconducting substrate;  
an electrode formed on the insulating layer; and  
at least one layer of graphene formed on the electrode and providing an electrical connection between the electrode and the substrate, wherein the nanostructure device is adapted to perform dual functions as a nano-switching/sensing device.

2. The nanostructure device of claim 1, wherein the at least one layer of graphene is formed on a top surface of the electrode and extends over an edge of the electrode and contacts the doped substrate to thereby form a Schottky diode.

3. The nanostructure device of claim 2, wherein when the dual function nano-switching/sensing device is exposed to a volatile gaseous species, the at least one layer of graphene adsorbs at least one molecule of the volatile gaseous species thereby altering an operation of the dual function nano-switching/sensing device to allow the nano-switching/sensing device to detect the presence of the volatile gaseous species.

4. The nanostructure device of claim 3, wherein when nano-switching/sensing device is removed from the volatile gaseous species, the at least one molecule of the volatile gaseous species is desorbed from the at least one layer of graphene and the nano-switching/sensing device returns to a normal mode of operation to thereby allow the nano-switching/sensing device to detect the absence of the volatile gaseous species.

5. The nanostructure device of claim 4, wherein the doped substrate is a silicon substrate doped with an n-type doping agent and has a silicon resistivity in the range of 1-10 ohms centimeter.

6. The nanostructure device of claim 4, wherein the doped substrate is a silicon substrate doped with a p-type doping agent and has a silicon resistivity in the range of 1-10 ohms centimeter.

7. The nanostructure device of claim 4, wherein the insulating layer is a silicon dioxide layer having a thickness of approximately 100-300 nm.

8. The nanostructure device of claim 4, wherein the electrode is an electrically conductive electrode.

9. The nanostructure device of claim 2, wherein when the Schottky diode is exposed to a gaseous volatile species, I-V characteristics of the Schottky diode are altered such that the Schottky diode detects the presence of the volatile gaseous species, and wherein when the Schottky diode is removed from the volatile gaseous species, the I-V characteristics of the Schottky diode reverse and return to their normal mode of operation such that the Schottky diode detects the absence of the volatile gaseous species.

10. The nanostructure device of claim 9, wherein the doped substrate is a silicon substrate doped with an n-type doping agent and has a silicon resistivity in the range of 1-10 ohms centimeter.

11. The nanostructure device of claim 9, wherein the doped substrate is a silicon substrate doped with a p-type doping agent and has a silicon resistivity in the range of 1-10 ohms centimeter.

12. The nanostructure device of claim 9, wherein the insulating layer is a silicon dioxide layer having a thickness of approximately 100-300 nm.

13. The nanostructure device of claim 9, wherein the electrode is a gold electrode.



9

14. The nanostructure device of claim 1, wherein the electrode formed on the insulating layer comprises at least two electrodes, wherein the at least one layer of graphene is formed on a top surface of the at least two electrodes and a semiconducting region between the at least two electrodes, and wherein a portion of the semiconducting region is etched such that a gaseous species to be sensed has direct physical access to both a top surface and a bottom surface of the at least one layer of graphene.

15. The nanostructure device of claim 14, wherein when the dual function nano-switching/sensing device is exposed to a volatile gaseous species, the at least one layer of graphene adsorbs at least one molecule of the volatile gaseous species thereby altering an operation of the dual function nano-switching/sensing device to allow the nano-switching/sensing device to detect the presence of the volatile gaseous species, and wherein when nano-switching/sensing device is removed from the volatile gaseous species, the at least one molecule of the volatile gaseous species is desorbed from the at least one layer of graphene and the nano-switching/sensing device returns to a normal mode of operation to thereby allow the nano-switching/sensing device to detect the absence of the volatile gaseous species.

16. A method of detecting a volatile gaseous species comprising:

providing a graphene-based nano-switching/sensing device where at least one layer of graphene provides an electrical connection between an electrode and a doped substrate where the electrode is disposed on the doped substrate;

10

exposing the nano-switching/sensing device to a volatile gaseous species;

adsorbing at least one molecule of the volatile gaseous species in the at least one layer of graphene;

altering the operation of the nano-switching/sensing device;

detecting the presence of the volatile gaseous species;

removing the nano-switching/sensing device from the volatile gaseous species;

desorbing the at least one molecule from the at least one layer of graphene;

reversing the operation of the nano-switching/sensing device; and

detecting the absence of the volatile gaseous species.

17. The method of claim 16, wherein the doped substrate is a silicon substrate doped with an n-type doping agent and has a silicon resistivity in the range of 1-10 ohms centimeter.

18. The method of claim 16, wherein the doped substrate is a silicon substrate doped with a p-type doping agent and has a silicon resistivity in the range of 1-10 ohms centimeter.

19. The method of claim 16, wherein an insulating layer comprised of silicon dioxide having a thickness of approximately 100-300 nm is disposed between the electrode and the doped substrate.

20. The method of claim 16, wherein the electrode is a gold electrode.

\* \* \* \* \*