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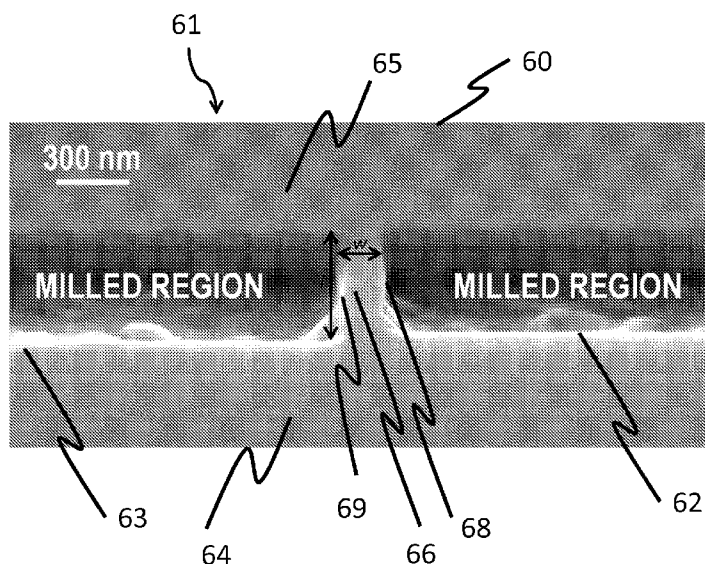


Fig. 6

(57) Abstract: The present invention may be embodied as a nanoscale semiconductor for broadband, room-temperature detection of electromagnetic radiation, including radiation in the microwave and terahertz regions of the spectrum. Radiation may be detected by utilizing intrinsic nonlinearities in the electrical characteristics of the nanosensor, such as drain conductance or transconductance. The nonlinearities generate either a measurable photo-current or photo-voltage by rectifying the incident electromagnetic radiation. The invention may involve utilizing the exchange of charge between surface states, formed at the etched walls of the nanosensor, and the interior of the nanosensor channel, as a way to generate the pronounced nonlinearities needed for efficient radiation detection.

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**RECTIFYING ELECTROMAGNETIC NANOSENSORS**

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**5 Cross-Reference to Related Application**

[0002] This application claims the benefit of priority to U.S. provisional patent application serial number 61/446,299, filed on February 24, 2011, now pending, the disclosure of which is incorporated herein by reference.

**Field of the Invention**

10 [0003] The present invention pertains to the use of nanoscale semiconductor devices as broadband, room-temperature detectors of electromagnetic radiation including radiation in the microwave and terahertz regions of the spectrum.

**Background of the Invention**

[0004] Bounded by the infrared and microwave regions, the terahertz (“THz”) portion  
15 of the electromagnetic spectrum is rich in potential applications, in commercial, medical, and security settings. Hampering the development of these applications, however, is a critical lack of key components, an issue often referred to as the “THz gap.” The ability of THz radiation to penetrate many materials without the potentially-damaging effects of high photon energy, typical of X-Rays, has made active THz imaging of vital interest for biometrics and security  
20 screening. While the past few years have witnessed significant advances in the development of stable THz sources, most notably quantum cascade lasers with tailored spectral output, there remains a serious shortage of sensors for use in THz imaging. Consequently, existing imaging systems typically only utilize a small number of detectors, and are forced to employ time-consuming scanning operation, thereby severely impacting their practicality.

25 [0005] The most common approaches to electromagnetic sensing with nanostructures have been based on the use of: resonant plasmon excitation by THz waves; bolometric

heating due to the radiation, and/or direct rectification of induced AC currents in nanosensors with nonlinear electrical characteristics.

[0006] The operation of previous plasmonic detectors is based on the resonant excitation of collective plasma oscillations by electromagnetic waves in the quasi-two-dimensional (2D) electron channel in field-effect transistors. Since both the electron density and velocity are modulated by the plasma wave, a DC source-drain photocurrent will develop in the channel, provided that it is asymmetrically biased. This photocurrent can therefore be used for detection of the radiation. The main advantage of such detectors arises from the resonant character of the interaction between the plasma wave and external radiation. Since the plasma frequency depends on the 2D electron density in the channel, and can be easily controlled by the gate voltage, this device can be potentially used as a tunable narrowband detector.

[0007] However, practical implementations of the plasmonic detector face a number of obstacles. Generation of the DC photo-current at plasma resonance is a nonlinear effect, which requires enhanced power levels of THz radiation, and strong coupling of this radiation to the plasmons. At THz frequencies, the wavelengths of the plasma and electromagnetic waves differ by a factor of about a hundred. Hence, achieving effective coupling of the THz radiation to the plasmons requires the use of elements such as a grating-gate coupler, or nanoscale gates with a special geometry. The use of these coupling elements causes a loss of the power delivered to the sample, reducing detector sensitivity. At elevated temperatures, increased plasmon damping due to phonon scattering results in significant broadening, and, ultimately, the disappearance of the plasma resonance, as a result of which the responsivity of these detectors drops significantly at temperatures above 40 K. Nonetheless, nonresonant broadband detection due to the modulation of the electron density and drift velocity has been observed in submicron FETs up to room temperatures. THz detection at room temperature was also observed in FETs interacting with 3D plasmons. In nonresonant detection, the detector operates in the diffusive regime ( $\omega\tau < 1$ , where  $\omega$  is the radiation frequency and  $\tau$  is the momentum relaxation time) and, quite generally, relaxation-time related restrictions then limit detection to frequencies below about 1 THz.

[0008] Bolometric detectors used with THz sources offer very high sensitivity and noise equivalent power, but typically require operation at cryogenic temperatures. In spite of the advantages of bolometric detection, its extension to higher temperatures is problematic due to the increased influence of the blackbody background at frequencies above 1 THz. In the temperature interval from 80 to 150 K, where THz detectors are often expected to operate, the maximum in the spectral density of the blackbody radiation ranges from 4.7 to 8.8 THz. Consequently, the increased blackbody noise in the interval of 1 – 10 THz sets a natural limit on the noise-equivalent power achievable with such detectors. The same reasoning holds for other types of detectors that operate on the direct absorption of THz energy, such as pyroelectric sensors and Golay cells. VOx microbolometer arrays, have been used to achieve standoff detection of the THz radiation emitted from quantum cascade lasers, over distances as long as 25 meters. These detectors also suffer from poor sensitivity beyond 1 THz, however, since they again require active illumination by powerful THz sources.

[0009] In contrast to bolometric detectors, sensors that utilize rectification of THz-induced AC voltages are largely unaffected by the blackbody background since such equilibrium radiation does not induce a net photovoltage/current. The most commonly used THz rectifiers are Schottky diodes, which operate at room temperatures and are widely used as detectors at radio and microwave frequencies. Their use for detection in the THz range is limited, however, for a number of reasons.

[0010] Due to the fact that they are planar tunnel structures, conventional Schottky diodes have large RC constants, and cutoff frequencies that generally fall below the THz range. Furthermore, the use of these diodes is typically restricted to zero-bias conditions, in spite of the fact that their responsivity increases under finite bias, where their current-voltage characteristics usually have larger nonlinearity. The reason for this zero-bias operation is that, when subject to finite bias, Schottky diodes tend to exhibit pronounced low-frequency noise arising from imperfections in the metal-semiconductor interface that defines their junction. As a result, Schottky THz detectors are not highly sensitive and are usually operated in heterodyne mode. Unlike direct detection, this mode of operation requires the use of a separate THz source that functions as a local oscillator. Due to a lack of such oscillators at

THz frequencies, the operational range of Schottky-diode detectors does not extend beyond 1 THz. Recently, some advances have been made to overcome these difficulties, by manufacturing various lateral nanostructures with diode-like DC response. At the same time, conventional Schottky diodes are being improved by using new materials to form lower Schottky barriers, and by optimizing current technology. In spite of these efforts, however, no advances in operation beyond 1 THz have been reported so far. Adding to these difficulties is the fact that the vertical nature of these structures does not make them amenable to easy integration into large CMOS circuits, such as image-processing arrays.

[0011] Utilizing surface states in nanostructures to achieve novel device operation has been explored previously. For example, the prior art has proposed an approach that uses a near-field charge (by a portion of the substrate) to effect the surface state to discharge and recharge the surface states for non-volatile memory applications. Others have emphasized the role of interfacial-state charging for the realization of memristor applications. In none of these studies, however, has surface-state engineering been used for rectification applications.

## Summary of the Invention

[0012] The invention may be embodied as an electromagnetic radiation detector. In one embodiment, the detector comprises a semiconductor substrate and at least one interrupt region.

[0013] The semiconductor substrate may be selected to form a depletion region at each boundary of the substrate. In one embodiment, the semiconductor substrate comprises a GaAs/AlGaAs heterostructure.

[0014] At least one interrupt region defines boundaries of a first substrate portion, a second substrate portion, and a channel substrate portion. The interrupt region(s) may be disposed in the substrate. The interrupt region(s) may be gates disposed on the substrate. In another embodiment, the gates may be formed from metal and supplied with a negative potential difference. The interrupt regions may be formed from a suitable material that forms a junction with the substrate resulting in a depletion region. For example, air, metal, doped-semiconductor, or other insulative materials may be used.

[0015] The channel substrate portion connects the first substrate portion and the second substrate portion. The channel substrate portion may have a width defined by the distance between a first channel boundary and a second channel boundary. In one embodiment, the width of the channel substrate portion may be defined by the shortest distance between the first channel boundary and the second channel boundary. For example, the width of the channel substrate portion may be between 100 nm and 300 nm. In another embodiment, the second channel boundary may be the edge or boundary of the substrate itself.

[0016] The channel substrate portion may also have a length defined by the distance between the first substrate portion and the second substrate portion. In another embodiment, the length of the channel substrate portion may be defined by the shortest distance between the first substrate portion and the second substrate portion. For example, the length of the channel substrate may be approximately 500 nm.

[0017] The width of the channel substrate portion may be selected such that a first depletion region formed at the first channel boundary overlaps with a second depletion region formed at the second channel boundary. The first and the second depletion regions may overlap when the potential difference across the length of the channel substrate portion is 0 volts. In one embodiment, the first and the second depletion regions overlap such that the electrical conductance along the length of the channel substrate portion is non-linear as a function of the potential difference across the length.

[0018] In another embodiment, the first and the second depletion regions may overlap when the detector is at room temperature. Room temperature may be defined as a temperature between and including 18 degrees to 22 degrees Celsius.

[0019] In one embodiment, the detector may further comprise a conductive gate layer. The conductive gate layer may be disposed on at least a part of the channel substrate portion and affect the electrical conductance of the channel substrate portion. In one embodiment, the conductive gate layer may be capacitively coupled with the channel substrate portion.

[0020] The invention may also be embodied as a method of detecting electromagnetic radiation in a target environment. The steps of the method may comprise providing a detector, biasing a first and/or second substrate portion, establishing a reference profile, exposing the detector to the target environment, measuring an electrical characteristic, and  
5 detecting electromagnetic radiation by comparing the measured electrical characteristic to the reference profile. In one embodiment, the frequency of the detected electromagnetic radiation may be between 1 THz and 10 THz.

[0021] The provided detector may have a semiconductor substrate and at least one interrupt region. The interrupt region(s) define boundaries of a first substrate portion, a  
10 second substrate portion, and a channel substrate portion. The interrupt region(s) may be disposed in the substrate. The interrupt region(s) may be gates disposed on the substrate. In another embodiment, the gates may be formed from metal and supplied with a negative potential difference. The interrupt region(s) may be formed from any suitable material that forms a junction with the substrate resulting in a depletion region. The channel substrate  
15 portion connects the first substrate portion and the second substrate portion. The channel substrate portion may have a width defined by the distance between a first channel boundary and a second channel boundary. The channel substrate portion may also have a length defined by the distance between the first substrate portion and the second substrate portion. The width of the channel substrate portion may be selected such that a first depletion region formed at  
20 the first channel boundary overlaps with a second depletion region formed at the second channel boundary. The first and the second depletion regions may overlap when the potential difference across the length of the channel substrate portion is 0 volts.

[0022] The detector may be exposed to the target environment and an electrical characteristic is measured between the first and second substrate areas.

25 [0023] In one embodiment, the biasing step may be performed on the first and/or second substrate portions. The biasing may be performed at different potentials or currents. For example, the biasing may be performed by varying the potential difference between the first substrate portion and the second substrate portion.

[0024] In another embodiment, the establishing step may establish a reference profile by measuring a baseline electrical characteristic between the first substrate portion to the second substrate portion when the device is exposed to ambient electromagnetic radiation. The electrical characteristic may be voltage and/or current.

5 [0025] The devices described here use nanoscale semiconductor devices as broadband, room-temperature detectors of electromagnetic radiation (including radiation in the microwave and terahertz regions of the spectrum). In such devices, radiation is detected by utilizing intrinsic nonlinearities in the electrical characteristics of the nanosensor, such as their drain conductance or transconductance. The nonlinearities generate either a measurable  
10 photo-current or photo-voltage, by rectifying the incident electromagnetic radiation. Such nanosensors function by utilizing the exchange of charge between surface states, formed at the etched walls of the nanosensor, and the interior of the nanosensor channel, as a way to generate the pronounced nonlinearities needed for efficient radiation detection.

[0026] Devices according to the present invention overcome many of the limitations  
15 identified above. Due to the classical nature of their rectification mechanism (further described below), the present devices are capable of exhibiting broadband THz response, particularly in the critical 1 – 10 THz range that is currently poorly served by previous technology. In contrast to detectors that rely on bolometric mechanisms, the present devices are immune to the influence of the blackbody background, allowing more sensitive detection  
20 to be achieved. The present devices also respond very quickly (on nanosecond timescales) to driving potentials, and are well-suited for applications requiring real-time processing, such as video-rate THz imaging. In contrast to Schottky diodes, the present devices are planar in their construction, making them far more amenable to multi-device integration for focal-plane imaging.

25 [0027] The present devices are useful for broad application in THz sensing, including active THz imaging in both commercial and military settings. Other applications lie in nondestructive evaluation, quality control and studies of atmospheric interactions.

Furthermore, the present devices are highly suited to integration into multi-element focal plane arrays, making them useful for application to real-time THz imaging systems.

### Brief Description Of The Drawings

[0028] For a fuller understanding of the nature and objects of the invention, reference  
5 should be made to the accompanying drawings and the subsequent description. Briefly, the drawings are:

Figure 1 illustrates a device in following with one embodiment of the invention;

Figure 2a illustrates a device in following with another embodiment  
10 of the invention;

Figure 2b illustrates conductance quantization of quantum point contacts with measurements of the conductance (in units of  $2e^2/h$ ) of a QPC at 2.5 K, illustrating the 1-D conductance quantization

Figure 3 illustrates a comparison of measured THz photo-response to fitting with a classical rectification model. The symbols in each panel show the measured change in THz at different temperatures (only 13% of measured data points are plotted in each panel);

Figure 4 illustrates THz induced photo-current at 1.45 K and 1.63 THz for several different values of  $V_g$  (indicated) in following with the invention;

Figure 5a illustrates a comparison of dark and irradiate  $I_d$ - $V_{sd}$  curves at 1.45 K and  $V_g = -5.6$  V.

Figure 5b illustrates similar measurements compared to Figure 5a in following with the invention for 2.45 THz and  $V_g = -5.35$  V;

Figure 6 illustrates a nanoscale channel, around 100 nm wide, realized in a 2DEG substrate by focused-ion-beam milling in keeping with the invention;

Figure 7 illustrates current-voltage characteristics in keeping with the invention measured at room temperature in nanoconstrictions approximately 500 nm long and of various widths (indicated);

Figure 8a illustrates current-voltage characteristics measured at room temperature for an 180 nm wide nanoconstriction in keeping with the invention, with (red) and without (blue) 2.5 THz irradiation;

Figure 8b illustrates THz photo-current calculated by subtraction of the “dark” current from that obtained with the THz irradiation present in Figure 7a; and

Figure 9 illustrates a method as one embodiment of the present invention.

### Further Description of the Invention

[0029] **Fig. 6** depicts an electromagnetic radiation detector **61** according to an embodiment of the present invention. The detector **61** comprises a semiconductor substrate **60** and at least one interrupt region (embodiments having two interrupt regions **62**, **63** are depicted in the figures). The semiconductor substrate **60** forms a depletion region at each boundary of the semiconductor substrate **60**. For example, a depletion region forms at the boundary of the interrupt regions **62**, **63** and the boundary of the semiconductor substrate **60** itself (the natural boundary). In an embodiment, the semiconductor substrate **60** comprises a GaAs/AlGaAs heterostructure. Other semiconductors, and combinations of semiconductors, that form depletion regions at boundaries are also suitable for use in embodiments of the invention.

[0030] The interrupt regions **62**, **63** define boundaries of a first substrate portion **65**, a second substrate portion **64**, and a channel substrate portion **66**. The channel substrate

portion **66** connects the first substrate portion **65** and the second substrate portion **64**. The interrupt regions **62, 63** may be disposed in the semiconductor substrate **60**. For example, the interrupt regions **62, 63** may be gaps in the semiconductor substrate **60** formed by removal of substrate material. Where the interrupt regions **62, 63** are disposed in the semiconductor substrate **60**, the interrupt regions **62, 63** may comprise any material which forms a boundary (e.g., a junction) causing the semiconductor to form a depletion region. For example, the interrupt regions **62, 63** may comprise a insulative material (e.g., air, etc.), metal, doped-semiconductor, or any other material that creates this effect (and combinations thereof).

[0031] In some embodiments, the interrupt regions **62, 63** may be gates disposed on the semiconductor substrate **60**. For example, the gates may be comprised of metal and layered on the semiconductor substrate **60**. Such gates are supplied with a negative potential, causing a depletion region to form due to the electrical charge on the gates.

[0032] In embodiments having two or more interrupt regions **62, 63**, the extents of the channel substrate portion **66** may be defined by the interrupt regions **62, 63**. For example, in the embodiment shown in **Fig. 6**, the detector **61** has a shape akin to an hour-glass (although symmetry is not a requirement). In other embodiments, for example, in embodiments having only one interrupt region, the extents of the channel substrate portion **66** may be defined by the interrupt region and the natural boundary of the semiconductor substrate **60** (a depletion region forming at the natural boundary).

[0033] The channel substrate portion **66** has a width  $w$  defined by the distance between a first channel boundary **68** and a second channel boundary **69**. The width  $w$  of the channel substrate portion **66** may be defined by the shortest distance between the first channel boundary **68** and the second channel boundary **69**. For example, where the first and second channel boundaries are curved, the width  $w$  may be selected as the shortest distance between such curved boundaries. In some embodiments, the width  $w$  of the channel substrate portion **66** is between 100 nm and 300 nm.

[0034] The channel substrate portion **66** also has a length  $l$  defined by the distance between the first substrate portion **65**, and the second substrate portion **64**. The length  $l$  of the

channel substrate portion **66** may be defined by the shortest distance between the first substrate portion **65** and the second substrate portion **64**. In some embodiments, the length  $l$  of the channel substrate portion **66** is approximately 500 nm.

[0035] The width  $w$  of the channel substrate portion **66** is selected such that a first depletion region formed at the first channel boundary **68** overlaps with a second depletion region formed at the second channel boundary **69** when the potential difference across the length of the channel substrate portion **66** is 0 volts. In this way, no voltage need be applied to the substrate portions (*e.g.*, no charge on the first and/or second substrate portions **65**, **64** adjacent to the channel substrate portion **66**) to achieve the interaction between the depletion regions. The potential of the first substrate portion **65** and second substrate portion **64** may be adjusted. Such adjustments include, without limitation, varying the potential difference between the first and second substrate portions **65**, **64** over time, varying the potential difference from a positive to a negative value, varying the potential difference from a negative to a positive value, and a combination of such adjustments.

[0036] The first and the second depletion regions may overlap such that the electrical conductance along the length  $l$  of the channel substrate portion **66** is non-linear as a function of the potential difference across the length  $l$ . In an embodiment, the first and the second depletion regions overlap when the detector **61** is at room temperature. Room temperature may be defined as a temperature between and including 18 degrees to 22 degrees Celsius.

[0037] In an embodiment, a conductive gate layer may be disposed on at least a part of the channel substrate portion **66**, the conductive gate layer being capacitively coupled to the channel substrate portion **66**. In this manner, the conductive gate layer may affect the electrical conductance of the channel substrate portion **66**.

[0038] **Fig. 9** depicts a method **90** of detecting electromagnetic radiation in a target environment according to an embodiment of the present invention. The steps of the method **90** comprise providing **91** a detector similar to the aforementioned detector, biasing **92** a first and/or second substrate portion of the detector, establishing **94** a reference

profile, exposing **96** the detector to the target environment, measuring **98** an electrical characteristic, and detecting **99** electromagnetic radiation by comparing the measured electrical characteristic to the reference profile. In an embodiment, the frequency of the detected electromagnetic radiation is between 1 THz and 10 THz.

5 [0039] The provided **91** detector has a semiconductor substrate and at least one interrupt region. The interrupt region(s) define boundaries of a first substrate portion, a second substrate portion, and a channel substrate portion. The interrupt region(s) may be disposed in the substrate. The interrupt region(s) may also be gates disposed on the substrate. In another embodiment, the gates may be formed from metal and supplied with a negative  
10 potential difference. The interrupt reasons may be any suitable material that forms a junction with the substrate resulting in a depletion region. A channel substrate portion connects the first substrate portion and the second substrate portion. The channel substrate portion may have a width defined by the distance between a first channel boundary and a second channel boundary. The channel substrate portion may also have a length defined by the distance  
15 between the first substrate portion and the second substrate portion. The width of the channel substrate portion may be selected such that a first depletion region formed at the first channel boundary overlaps with a second depletion region formed at the second channel boundary. The first and the second depletion regions may overlap when the potential difference across the length of the channel substrate portion is 0 volts.

20 [0040] The detector may be exposed **96** to the target environment and an electrical characteristic may be measured **98** between the first and second substrate areas.

[0041] In an embodiment, the biasing **92** step may be performed on the first and/or second substrate portions. The biasing **92** may be performed at different potentials or currents. For example, the biasing may be performed by varying the potential difference  
25 between the first substrate portion and the second substrate portion. As another example, the voltage or current value may be swept from positive to negative, and negative to positive.

[0042] In another embodiment, the establishing **94** step may establish a reference profile by measuring a baseline electrical characteristic between the first substrate portion and

the second substrate portion when the device is exposed to ambient electromagnetic radiation. The electrical characteristic may be voltage and/or current. Electromagnetic radiation may be detected **99** by comparing the measured **98** electrical characteristic to the reference profile. For example, the reference profile may be subtracted from the measured electrical  
5 characteristic, the results indicating the presence of electromagnetic radiation on the sensor. **Fig. 8a** and **Fig. 8b** are an example of one such comparison.

[0043] Further reference is made to the following explanation and non-limiting example embodiments of the devices and methods described above.

[0044] **Fig. 2a** depicts a Quantum Point Contact. Quantum Point Contacts (QPCs) are  
10 nanoelectronic devices realized by using nanofabrication techniques to deposit metal gates **20, 24**, separated by a nanoscale gap, on the surface of a high-mobility semiconductor **26**. In some embodiments, the gap may be approximately 100nm. By applying a negative bias ( $V_g$ ) to the gates **20, 24**, electrons in the semiconductor **26** underneath them are depleted and current flow is then restricted to the nanoscale gap. Critical to understanding the application  
15 of QPCs to THz detection is the nature of the self-consistent potential that is induced in the semiconductor by the split-gate voltage, which raises the conduction-band locally in the vicinity of the constriction, forming a two-dimensional saddle barrier. This barrier confines electrons as they pass through the QPC, and so quantizes their transverse momentum to form a series of one-dimensional (1D) subbands. At the same time, the saddle potential also  
20 presents a local barrier to current flow. By varying the gate voltage, both the degree of the transverse confinement, and height of the local barrier, can be tuned in situ, and this tunability is crucial to the use of QPCs for THz detection.

[0045] At cryogenic temperatures ( $< 4.2$  K), thermal energy is smaller than the 1D subband separation, and the mean-free path is sufficiently long to ensure that electron  
25 transport through the QPC is ballistic. It is the combination of ballistic transport and strong subband quantization that results quantization of the conductance in 1D. An example of this quantization is shown in **Fig. 2b**. The graph of **Fig. 2b** shows the variation of the QPC conductance as a function of gate voltage ( $V_g$ ) at 2.5 K. As  $V_g$  is made more negative, the

transverse confinement within the QPC grows, and the conductance decreases in a step-like fashion as the number of 1D subbands occupied by electrons decreases one at a time. This is the regime of multi-subband 1D transport, which typically washes out around a few Kelvin as the thermal energy becomes comparable to the energy spacing ( $\sim \text{meV}$ ) of the 1D subbands.

5 As the gate voltage is made even more negative (than  $-3.1 \text{ V}$  in Fig. 2), the lowest subband is eventually pushed above the Fermi level in the source and drain region and the conductance vanishes (the device pinches off). In this regime, current flow from source to drain is limited by the barrier within the QPC, through which electrons may either tunnel or undergo thermal activation.

10 [0046] The invention may utilize a result in the multi-subband regime. Namely, the strongly non-linear nature of the transconductance, arising from its 1D quantization (see Fig. 2b), can give rise to a pronounced, rectification-induced, photo-current. An example of this photo-response is shown in Fig. 3, in which the THz-induced photo-current ( $\Delta I_{\text{THz}}$ ) is plotted as a function of  $V_g$  (data are for a different device to that of Fig. 2a). At the lowest

15 temperature,  $\Delta I_{\text{THz}}$  shows a clear series of oscillations, which were found to be correlated to the transitions between successive quantized steps; that is, to the regions of maximum non-linearity in the transconductance. Through a series of detailed experiments, bolometric heating, or photon-induced subband transitions were ruled out as the source of this photo-response. Instead, these results are consistent with a classical model of rectification. The key

20 idea of such a model is that THz radiation incident on the device can induce a time-dependent variation of both the source-drain and gate voltages. While the time average of either of these modulations will be equal to zero, it should be noted that this does not necessarily imply that the resulting photo-current will be similarly zero. Notably, in a situation where the QPC current varies non-linearly as a function of either  $V_g$  or source voltage ( $V_{sd}$ ), a rectified photo-

25 current will be obtained. To describe this effect quantitatively, we assume that the THz field induces modulations  $\delta V_g$  &  $\delta V_{sd}$ , and phenomenologically write the THz induced correction to the QPC current in the form of a power series (Eq. 1):

$$\Delta I_{\text{THz}} = \frac{1}{2} \frac{\partial^2 I}{\partial V_{sd}^2} \langle \delta V_{sd}^2 \rangle + \frac{\partial^2 I}{\partial V_{sd} \partial V_g} \langle \delta V_g \delta V_{sd} \rangle + \frac{1}{2} \frac{\partial^2 I}{\partial V_g^2} \langle \delta V_g^2 \rangle + \dots$$

where  $\langle \dots \rangle$  denotes time averaging over the THz period. Note that the terms proportional to odd powers of  $\delta V_g$  and  $\delta V_{sd}$  vanish on averaging over the THz period and so are not included in Eq. 1. By assuming that the QPC is in the regime of linear conductance ( $\partial I / \partial V_{sd} = I / V_{sd}$ ),  
 5 and that the relative modulation of  $V_g$  is small ( $\delta V_g \ll V_g$ ), Eq. 1 reduces to Eq. 2:

$$\Delta I_{\text{THz}} \approx \alpha \frac{\partial I}{\partial V_g} + \beta \frac{\partial^2 I}{\partial V_g^2},$$

where  $\alpha = \langle \delta V_g \delta V_{sd} \rangle / V_{sd}$ , and  $\beta = \langle \delta V_g^2 \rangle / 2$ . The form of Eq. 2 confirms that the photo-response due to this mechanism is expected to be maximal for regions where the current exhibits pronounced non-linearity as a function of gate voltage. **Fig. 3** shows the result of  
 10 fitting our measured data for  $\Delta I_{\text{THz}}$  to Eq. 2 using  $\alpha$  and  $\beta$  as fitting parameters. The fits (solid lines) were obtained by numerical differentiation of the experimental  $I$ - $V_g$  curves and the fact that they account excellently for the behavior observed at each temperature, and over the entire  $V_g$  range, suggests our approach is appropriate. These results provide convincing evidence that rectification of the effective gate voltage is, indeed, the relevant mechanism in  
 15 the invention. Although the results of **Fig. 3** are for a THz frequency of 1.4 THz, photo-response at 2.5 THz has been measured with no noticeable decrease in sensor responsivity.

[0047] As the temperature is increases in **Fig. 3**, the photo-response decreases in magnitude, although the main peak near -4.7 V remains noticeably robust. The general suppression of this response can be attributed to the fact that, with increasing temperature, the  
 20 quantized staircase in the QPC conductance washes out, and it is this weakening of the non-linearity in the transconductance that is responsible for the suppression of the photo-current (see Eq. 2).

[0048] The invention may utilize THz irradiation on the electrical characteristics in the barrier-limited regime, where the QPC is pinched-off and thermal activation over its local  
 25 barrier is the main mechanism for current flow. In this regime, an  $I_d$ - $V_{sd}$  curve of the QPC was measured at different fixed gate voltages. Modifications to the curve due to THz

irradiation were studied. Under dark conditions, the current exhibits a region near zero bias where it is strongly suppressed, due to the presence of the local barrier, but at larger  $V_{sd}$  it increases significantly due to an associated lowering of this barrier.

[0049] Representative results from THz measurements are presented in **Figs. 4, 5a,**  
5 **and 5b.** **Fig. 5a** shows  $I_d$ - $V_{sd}$  curves measured with and without THz irradiation (at 1.63 THz). These data are for a fixed gate voltage of -5.6 V. In **Fig. 4**, the THz photo-current obtained by the subtraction of these two curves is plotted, along with similar measurements at other gate voltages. Reproducible step-like features are apparent in all of the curves. These features are correlated with the population of successive 1D subbands of the QPC, as the  
10 increasing source voltage pulls down the QPC barrier. This photo-response can largely be attributed to a bolometric effect (i.e. laser-induced heating), which can be even stronger than any rectification in this regime of activated transport.

[0050] The strongly non-linear character of transport in nanoconstrictions can give rise to significant THz photo-response. Physically, this response was found to arise from both  
15 rectification-based and bolometric mechanisms, with the latter dominating at low temperatures when the device is pinched-off.

[0051] With increasing temperature, however, the non-linearity of these devices is suppressed, a trend that is accompanied by a reduction in detection efficacy. While this suppression generally makes QPCs unsuited for use as room-temperature detectors of THz  
20 radiation, their low-temperature capabilities nonetheless indicate a useful approach to sensor realization. Most notably, although the non-linearity of these devices (**Fig. 2a**) is quantum-mechanical, the rectification that it leads to is essentially a classical effect. This mechanism is therefore not expected to be strongly sensitive to frequency, or to the black-body background, and allows for THz detection at much higher temperatures (i.e. room temperature), at least in  
25 devices with appropriately-robust non-linearities. Devices according to embodiments of the present invention, utilize strong lateral carrier confinement, leading to pronounced electrical non-linearities that are robust even in the presence of the thermal fluctuations present at room temperature.

[0052] Devices according the present invention utilize the low (meV) photon energy of THz waves, a characteristic that makes such waves well suited to stand-off materials evaluation and security screening—applications where it is desirable to avoid the use of ionizing radiation such as X-rays. The short wavelength ( $<10^2 \mu\text{m}$ ) of THz photons also makes them well suited for imaging applications, where they can provide enhanced resolution as compared to longer-wavelength microwaves. In addition, in order to take advantage of the low-cost manufacturing processes of modern nanoelectronics, devices according to embodiments of the present invention can be implemented in a CMOS process flow, or are, at least, compatible with CMOS manufacturing.

[0053] Devices according to embodiments of the present invention may comprise semiconductor nanoconstrictions in which strong lateral confinement of the carriers, combined with electrostatic gating, will allow the creation of highly non-linear features in their electrical characteristics. Such non-linearities may be exploited to achieve efficient THz rectification. The ability to induce such strong electrical non-linearities may significantly improve detector responsivity, while at the same time also lower noise equivalent power (“NEP”), which describes the minimum signal power distinguishable from signal noise. In addition, the lateral structure of the sensors will make them amenable to integration into large CMOS circuits, such as image-processing arrays.

[0054] In embodiments of the invention, nanoconstrictions (channel substrate portions) are realized by using suitable nanolithography approaches to implement a channel, around 500-nm long and of width 100 – 400 nm, in the high-mobility 2DEG of a GaAs/AlGaAs heterostructure. The nanoconstriction may be fabricated by using wet chemical etching to transfer the desired pattern to the substrate and using electron-beam lithography to expose the desired pattern. In another fabrication method, focused-ion-beam milling may be used to implement a one-step process in which excess material is milled away to form the interrupt regions in the substrate and thereby forming the channel substrate portion. Both approaches provide a reliable method of fabricating suitable devices, although the focused-ion-beam method allows for more precise control of the device dimensions. An

example of a nanoconstriction fabricated by ion-beam milling is shown in **Fig. 6**. Other techniques for fabricating similar structures in semiconductive material may be utilized.

[0055] The DC electrical characteristics of several different exemplary nanoconstrictions have been investigated by applying a variable source-drain voltage ( $V_{sd}$ ) and measuring the variation of the resulting current ( $I_d$ ). It should be noted that the first and second substrate portions can be a source ( $s$ ) and drain ( $d$ ) with the channel substrate portion (nanoconstriction) connecting the source and the drain. For further insight into the physical mechanisms of conduction, these characteristics were also measured for a variety of temperatures between 77 & 300 K in the exemplary devices. In **Fig. 7**, the influence of channel width ( $W_e$ ) on conduction is demonstrated by comparing the room-temperature  $I_d$ - $V_{sd}$  curves for three different devices with  $W_e = 350\text{nm}$ ,  $180\text{nm}$  &  $130\text{nm}$ .

[0056] In the exemplary devices, there was a clear tendency for the magnitude of the current to decrease with reduction of the channel width, consistent with an associated increase in the resistance of the nanoconstriction. For the widest channel, the value of the resistance near  $V_{sd} = 0$  is in excess of  $500\text{ k}\Omega$ , indicating that the channel is essentially pinched-off. The value of this resistance increases to  $\text{G}\Omega$  order for the narrowest channel studied, and this overall trend among the different devices can be understood to arise from the influence of Fermi-level pinning at the exposed channel walls. The pinning is accompanied by the formation of a depletion region that extends into the interior of the semiconductor. As the width of the etched channel is reduced, the depletion regions formed at its exposed walls overlap more and more, and it is this effect that is responsible for the associated dramatic increase in channel resistance implied by **Fig. 7**.

[0057] From the viewpoint of THz detection, the curves of **Fig. 7** indicate the presence of robust non-linearity that persists even at room temperature. Although not apparent on the scale of **Fig. 7**, the data for the  $130\text{ nm}$  constriction also exhibit strong non-linearity. Measurements have been performed on a  $180\text{ nm}$  width constriction. The measurements were made at room temperature, using a  $\text{CO}_2$  gas laser to pump methanol gas and generate radiation at  $2.5\text{ THz}$ . With an emphasis on providing a proof-of-principle

demonstration, measurements were made with a simple setup in which the test device was placed, while subject to ambient room illumination, in the path of the unfocused THz beam. These results, as illustrated in **Fig. 8a**, determine the THz photo-current by measuring the  $I_d$ - $V_{sd}$  curve for the device both in the absence of, and under, THz illumination **Fig. 8a**. It should  
5 be noted that these curves are distinct from that shown in **Fig. 7**, which was obtained for a similar device but without ambient room illumination. **Fig. 8b** shows the photo-current obtained by subtraction of these two measurements, and reveals a significant response to the THz irradiation. This response is maximal near  $\pm 4$  V (around  $0.5 \mu\text{A}$ ), where the current reaches a plateau like feature, but is of opposite polarity to that of the current itself. Also  
10 apparent is a similarly large photo-response near  $\pm 16$  V, which is associated with a reproducible hysteresis that appears in both curves (each  $I_d$ - $V_{sd}$  curve actually includes measurements obtained while sweeping  $V_{sd}$  both backwards and forwards).

[0058] Embodiments of devices according to the present invention may include integrating a local nanoscale gate to achieve an additional, rectification-based, modulation of  
15 the detector current.

[0059] **Fig. 1** illustrates an embodiment of a device according to the present invention. In this embodiment, three interrupt regions **10, 14, 18** form a nanoscale gap **12**.

[0060] Embodiments of devices according to the present invention may include impedance-matched antenna structures to efficiently couple radiation to the detector.

20 [0061] Although the present invention has been described with respect to one or more particular embodiments, it will be understood that other embodiments of the present invention may be made without departing from the spirit and scope of the present invention. Hence, the present invention is deemed limited only by the appended claims and the reasonable interpretation thereof.

25

What is claimed is:

1. An electromagnetic radiation detector, comprising:

a semiconductor substrate, wherein the semiconductor substrate forms a depletion region at each boundary of the substrate;

5 at least one interrupt region defining boundaries of a first substrate portion, a second substrate portion, and a channel substrate portion connecting the first substrate portion and the second substrate portion; the channel substrate portion having a width defined by the distance between a first channel boundary and a second channel boundary, and a length defined by the distance between the first substrate portion and the second substrate portion; and

10 wherein the width of the channel substrate portion is selected such that a first depletion region formed at the first channel boundary overlaps with a second depletion region formed at the second channel boundary when the potential difference across the length of the channel substrate portion is 0 volts.

15

2. The detector of claim 1, wherein the at least one interrupt region is disposed in the substrate.

20

3. The detector of claim 1, wherein the at least one interrupt region comprises a gate disposed on the substrate.

4. The detector of claim 1, wherein the first and the second depletion regions overlap such that the electrical conductance along the length of the channel substrate portion is non-linear as a function of the potential difference across the length.

25

5. The detector of claim 1, wherein the first and the second depletion regions overlap at when the detector is at room temperature.

6. The detector of claim 1, wherein the width of the channel substrate portion is defined by the shortest distance between the first channel boundary and the second channel boundary.

5 7. The detector of claim 1, wherein the width of the channel substrate portion is between 100 nm and 300 nm.

8. The detector of claim 1, wherein the length of the channel substrate portion is defined by the shortest distance between the first substrate portion and the second substrate portion.

10

9. The detector of claim 1, wherein the length of the channel substrate portion is approximately 500 nm.

10. The detector of claim 1, wherein the at least one interrupt region comprises air.

15

11. The detector of claim 1, further comprising a conductive gate layer disposed on at least a part of the channel substrate portion, the conductive gate layer being capacitively coupled to the channel substrate portion.

20 12. The detector of claim 1, wherein the substrate comprises a GaAs/AlGaAs heterostructure.

13. A method of detecting electromagnetic radiation in a target environment, comprising the steps of:

providing a detector having:

25 a semiconductor substrate, wherein the semiconductor substrate forms a depletion region at each boundary of the substrate;

at least one interrupt region defining boundaries of a first substrate portion, a second substrate portion, and a channel substrate portion connecting the first substrate portion and the second substrate portion; the channel substrate portion having a width defined by the distance between a first channel

30

boundary and a second channel boundary, and a length defined by the distance between the first substrate portion and the second substrate portion; and wherein the width of the channel substrate portion is selected such that a first depletion region formed at the first channel boundary overlaps with a second depletion region formed at the second channel boundary when the potential difference across the length of the channel substrate portion is 0 volts; biasing the first and/or second substrate portions to different potentials; establishing a reference profile by measuring a baseline electrical characteristic between the first substrate portion to the second substrate portion when the device is exposed to ambient electromagnetic radiation; exposing the detector to the target environment; measuring an electrical characteristic between the first and second substrate areas; and detecting electromagnetic radiation by comparing the measured electrical characteristic to the reference profile.

14. The method of claim 13, wherein the at least one interrupt region is disposed in the substrate.

15. The method of claim 13, wherein the at least one interrupt region comprises a gate disposed on the substrate.

16. The method of claim 13, wherein the electrical characteristic is current and/or voltage.

17. The method of claim 13, wherein the electrical characteristic is current.

18. The method of claim 13, wherein the biasing is performed by varying the potential difference between the first substrate portion and the second substrate portion.

19. The method of claim 13, wherein the frequency of the detected electromagnetic radiation is between 1 THz and 10 THz.

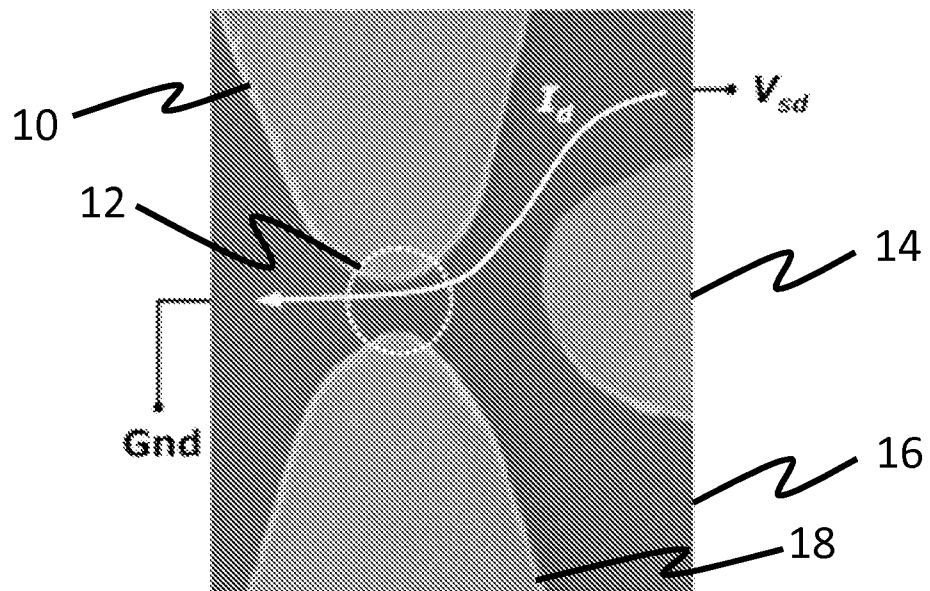


Fig. 1

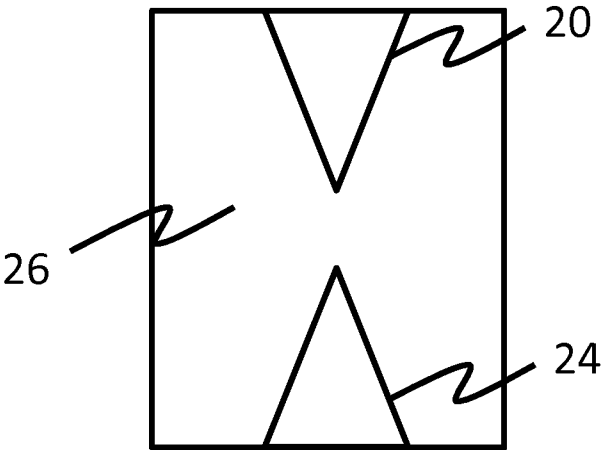


Fig. 2a

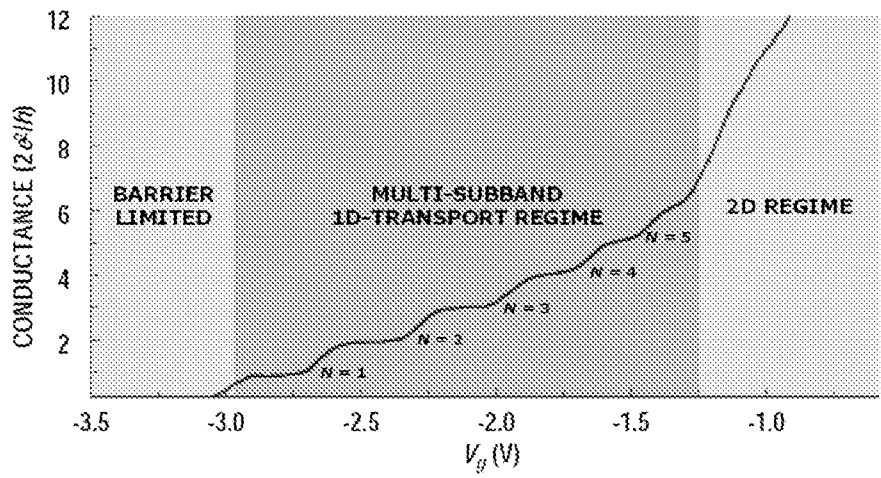


Fig. 2b

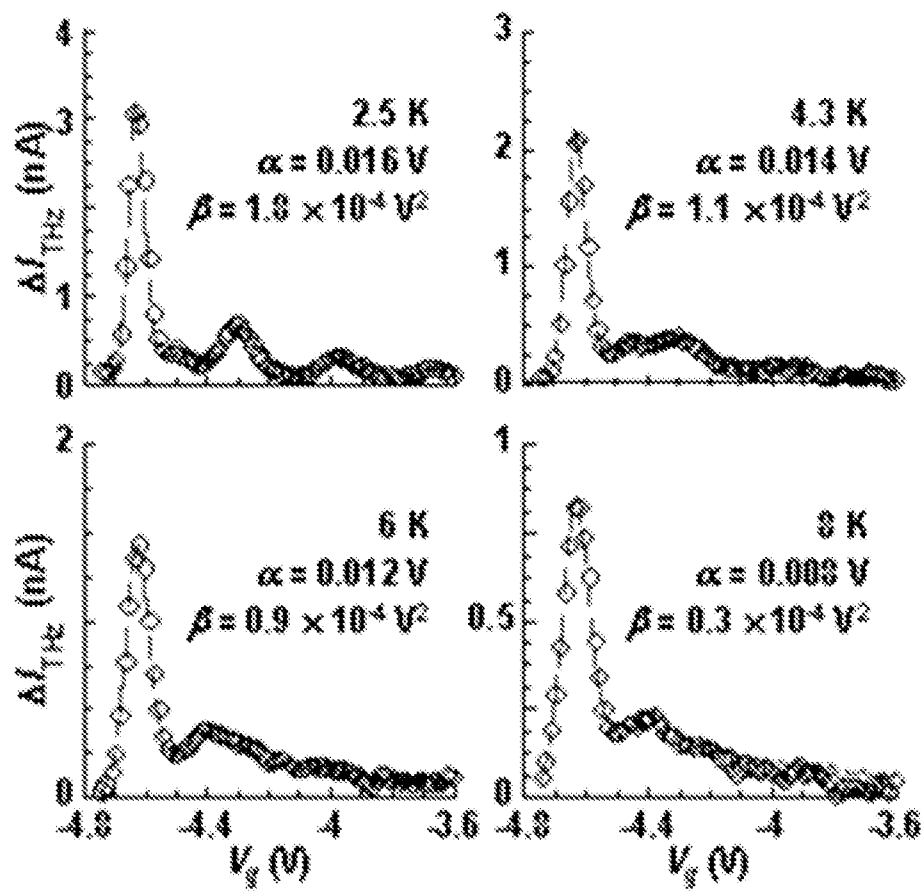


Fig. 3

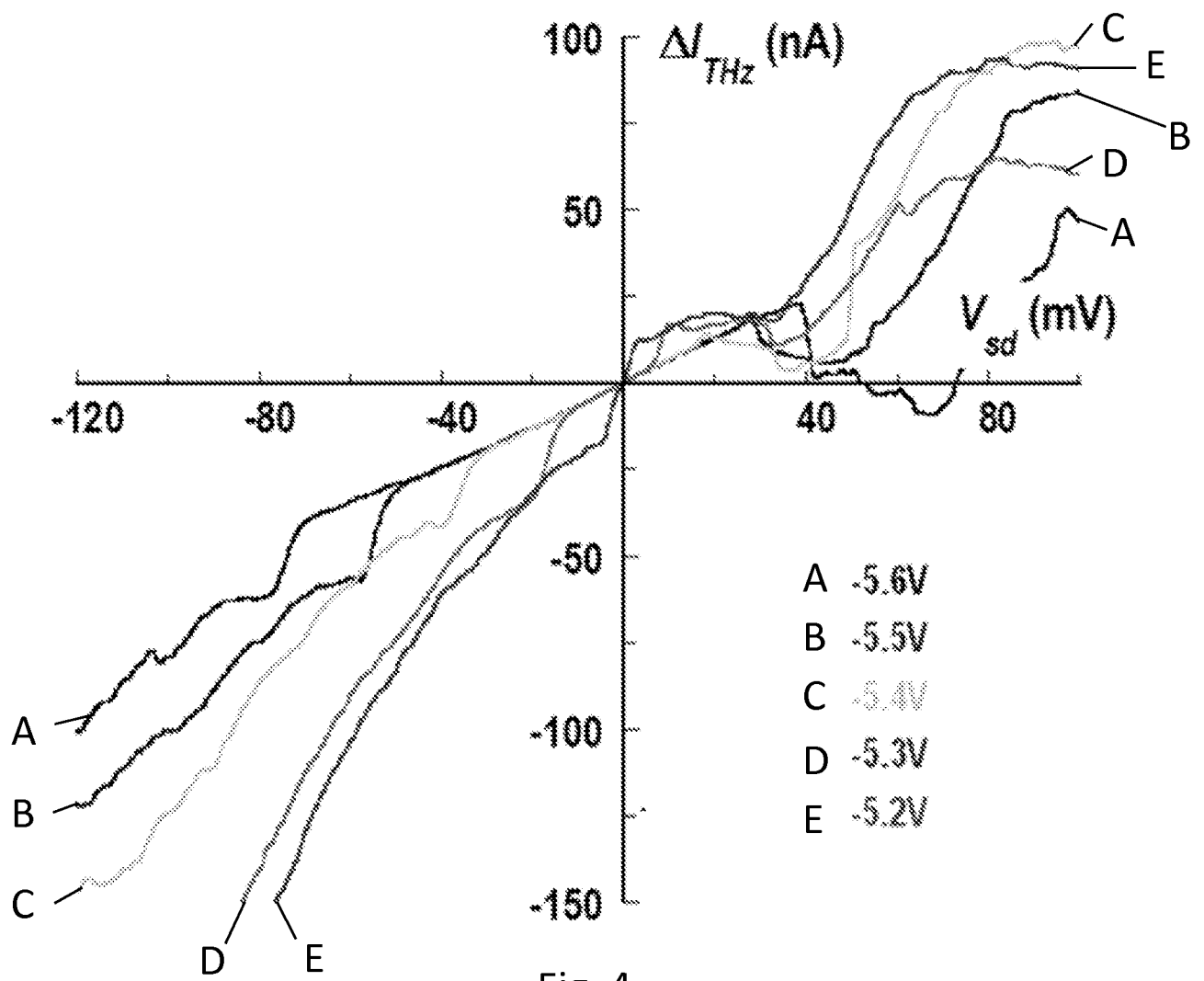


Fig. 4

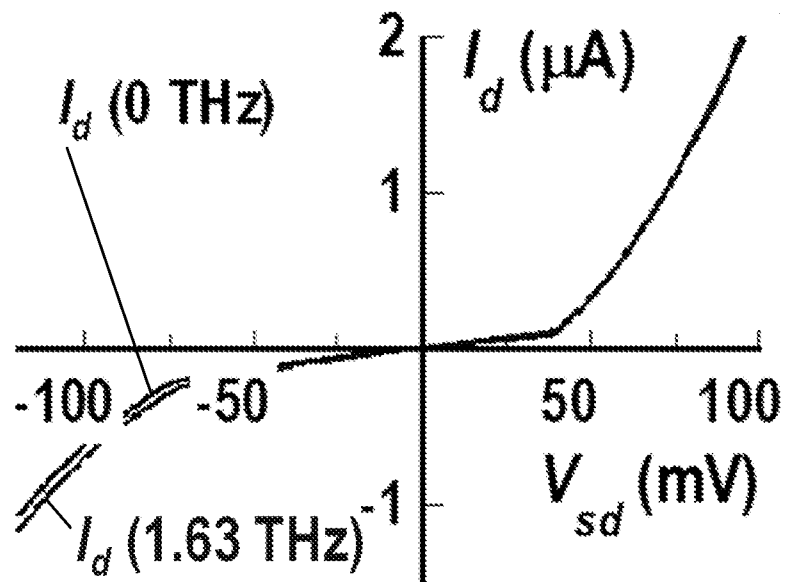


Fig. 5a

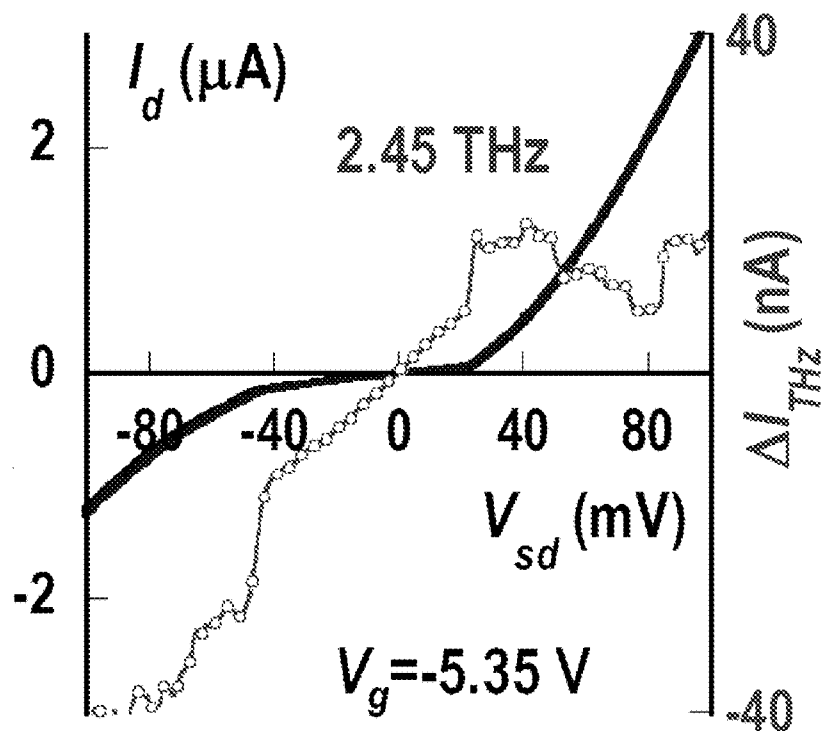


Fig. 5b

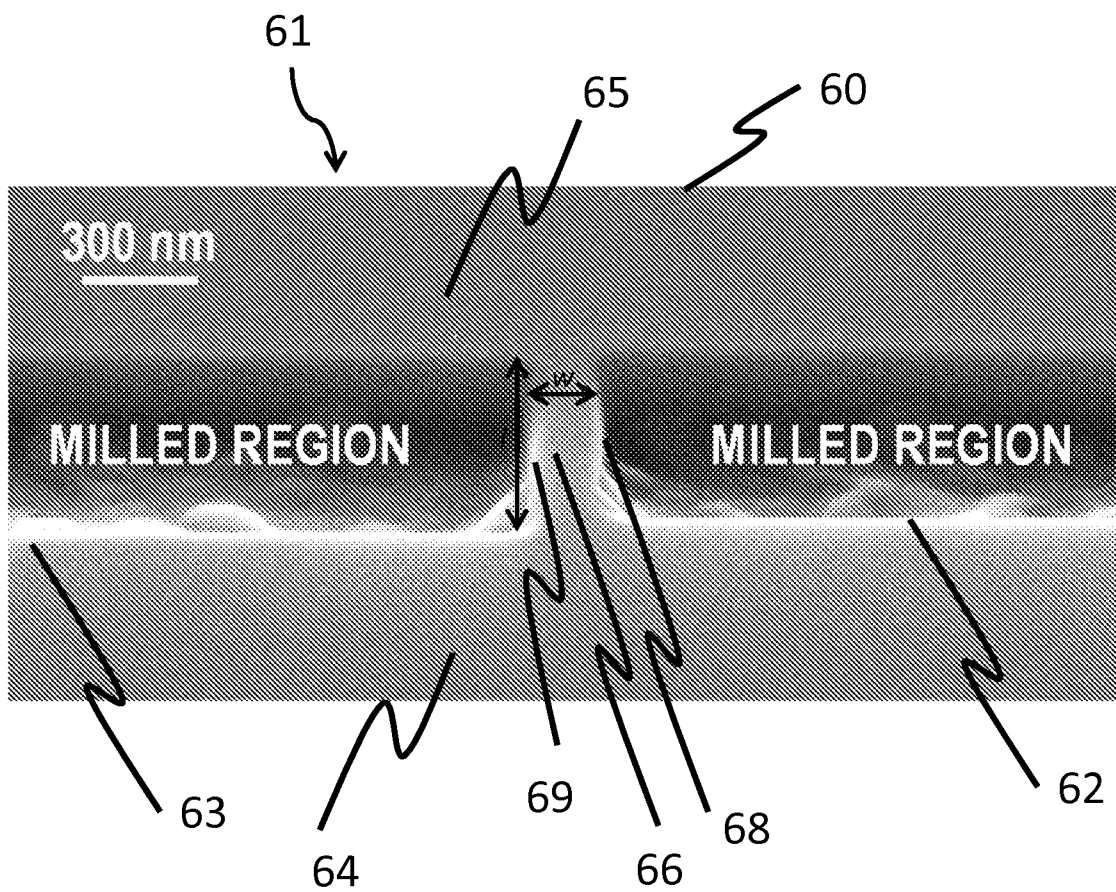


Fig. 6

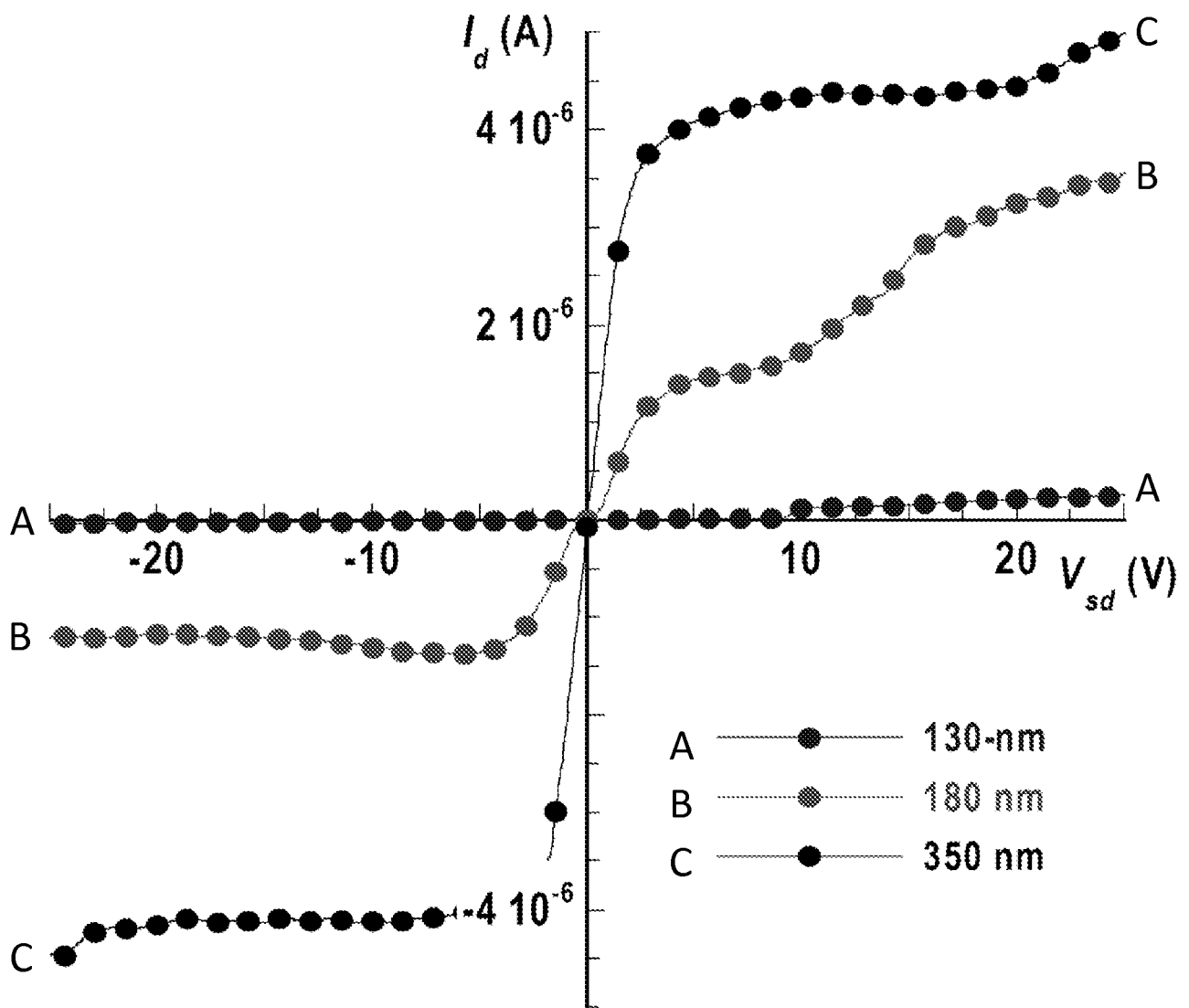


Fig. 7

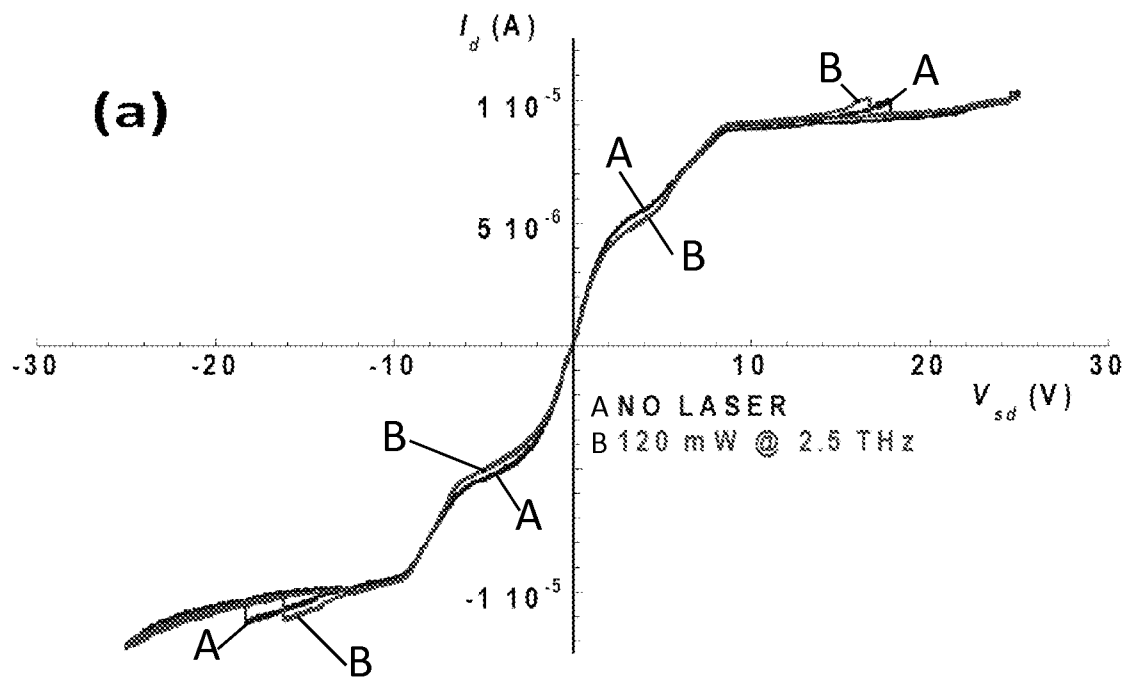


Fig. 8a

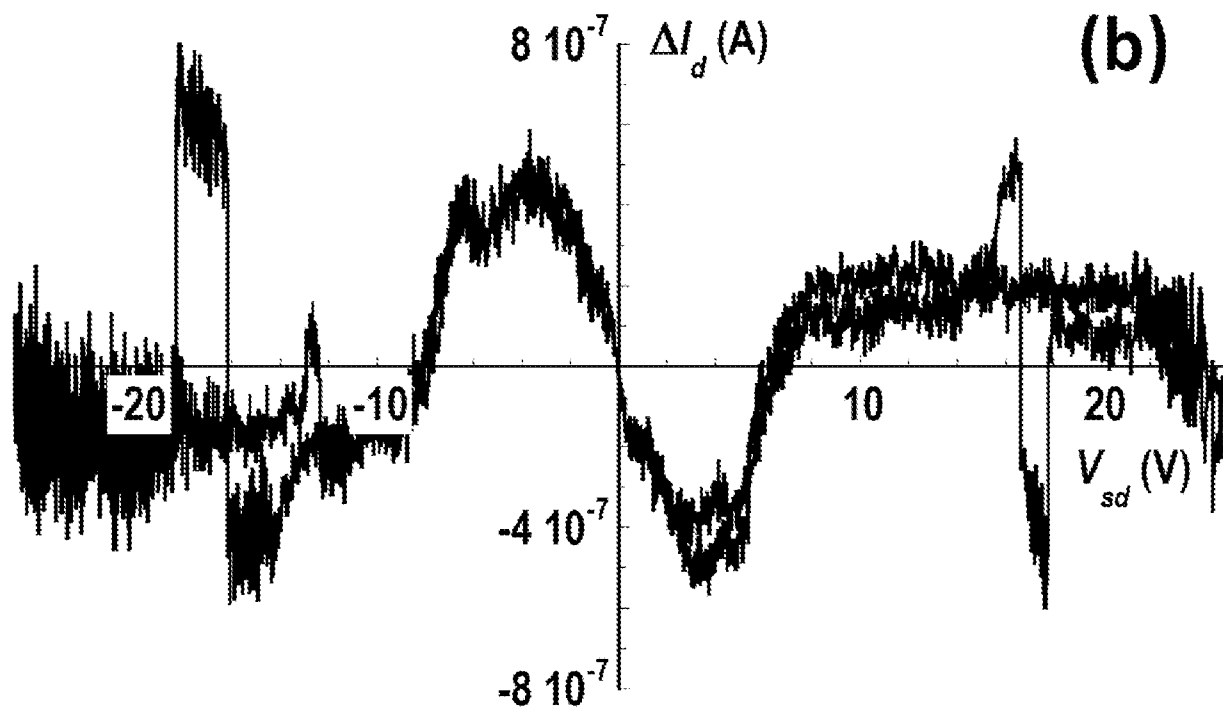


Fig. 8b

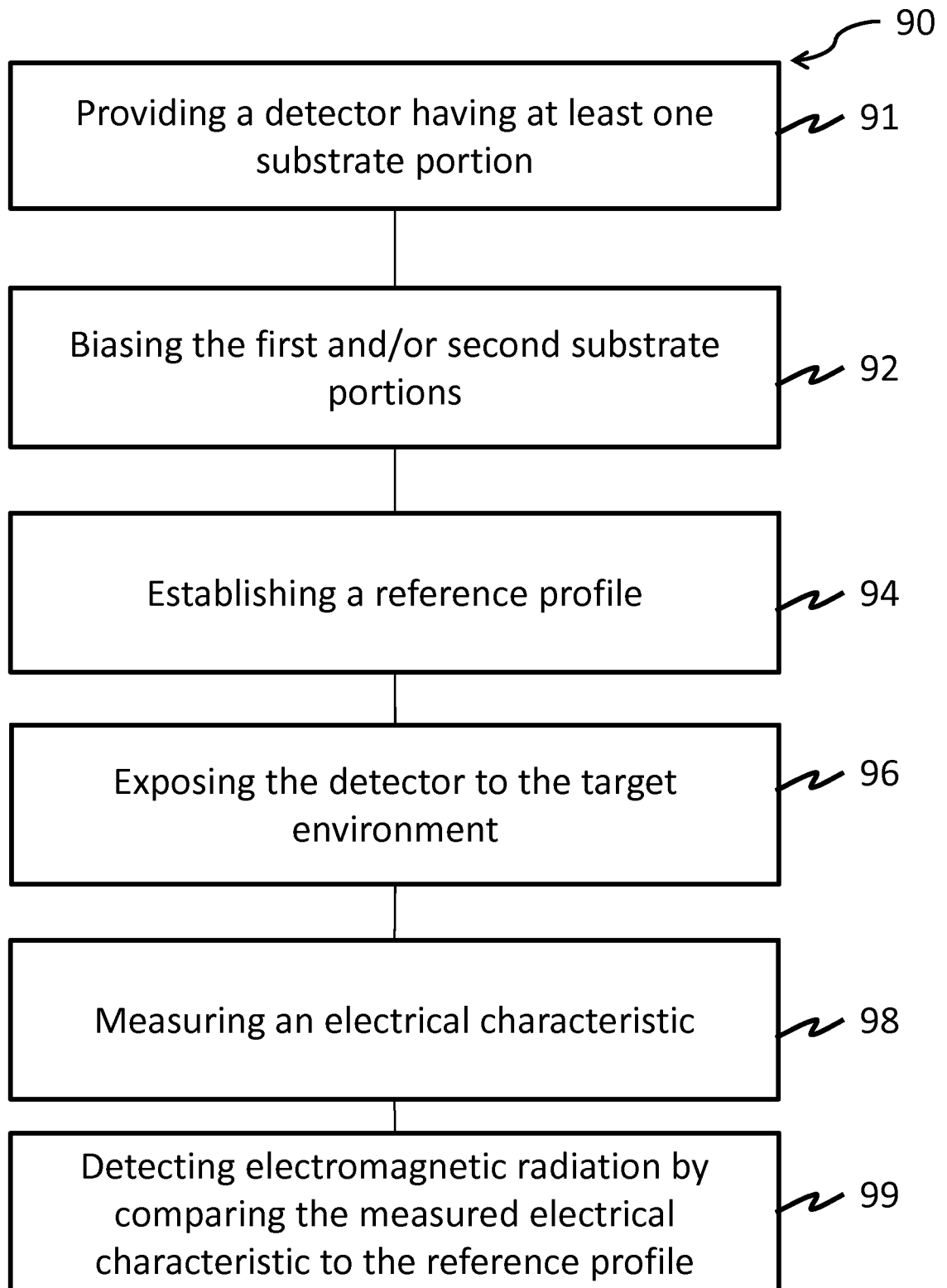


Fig. 9