



(51) International Patent Classification:

H01L 31/0232 (2014.01) H01L 31/105 (2006.01)

H01L 31/0304 (2006.01)

(21) International Application Number:

PCT/SG2018/050446

(22) International Filing Date:

04 September 2018 (04.09.2018)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

10201707146W 04 September 2017 (04.09.2017) SG

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA,

(54) Title: PHOTODETECTOR

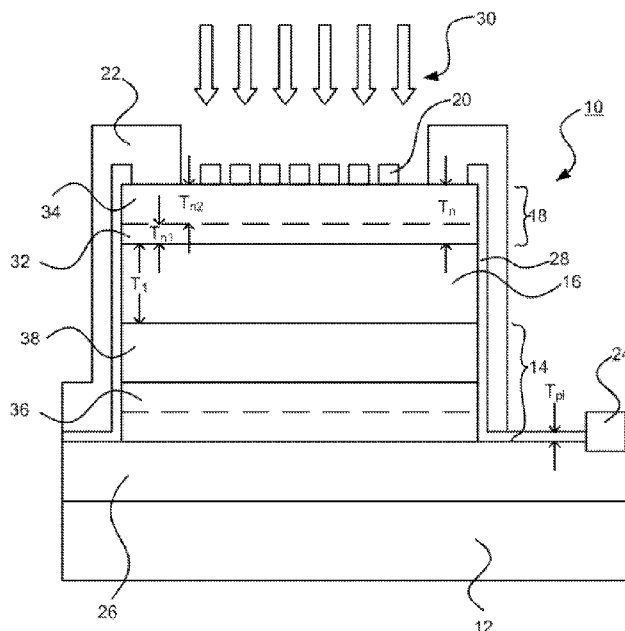


FIG. 1

(57) Abstract: A photodetector (10) is provided. The photodetector (10) includes a substrate (12), a p-type semiconductor region (14) on the substrate (12), an intrinsic semiconductor region (16) on the p-type semiconductor region (14), an n-type semiconductor region (18) on the intrinsic semiconductor region (16), a surface plasmonic structure (20) on the n-type semiconductor region (18), a cathode (22) electrically connected to the n-type semiconductor region (18), and an anode (24) electrically connected to the p-type semiconductor region (14).

SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN,
TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

- (84) Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

- *of inventorship (Rule 4.17(iv))*

Published:

- *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

PHOTODETECTOR

Field of the Invention

The present invention relates to the field of microelectronics and more particularly to a photodetector.

5 Background of the Invention

Photodetectors are widely used in fields of spectroscopy, biological monitoring and imaging. Limitations of conventional photodetectors include, for example, cryogenic temperature operation and low quantum efficiency.

It is therefore desirable to provide a photodetector with improved performance at
10 room temperature.

Summary of the Invention

Accordingly, in a first aspect, the present invention provides a photodetector, including: a substrate; a p-type semiconductor region on the substrate; an intrinsic semiconductor region on the p-type semiconductor region; an n-type semiconductor region
15 on the intrinsic semiconductor region; a surface plasmonic structure on the n-type semiconductor region; a cathode electrically connected to the n-type semiconductor region; and an anode electrically connected to the p-type semiconductor region.

Other aspects and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings,
20 illustrating by way of example the principles of the invention.

Brief Description of the Drawings

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

FIG. 1 is a schematic cross-sectional view of a photodetector in accordance with an
25 embodiment of the present invention;

FIG. 2A is a schematic perspective view of a surface plasmonic structure in accordance with an embodiment of the present invention;

FIG. 2B is a schematic top plan view of the surface plasmonic structure of FIG. 2A;

FIG. 3 is a scanning electron microscope (SEM) image taken from the top of a
5 photodetector in accordance with an embodiment of the present invention;

FIGS. 4A through 4D are scanning electron microscope (SEM) images of two-dimensional subwavelength hole array (2DSHA) surface plasmonic structures with different periods;

FIG. 5 is a graph of the penetration depth of surface plasmon resonance (SPR) in
10 the photodetector;

FIGS. 6A through 6D are graphs of the photocurrent spectra of photodetectors with and without surface plasmonic structures having different periods under zero bias at 293 kelvin (K);

FIGS. 7A through 7D are graphs of the photocurrent spectra of photodetectors with
15 and without surface plasmonic structures having different periods under zero bias at 77 K;

FIG. 8 is a graph of the relative spectral response of the photodetector of FIG. 3 under zero bias at 77 K and 293 K;

FIGS. 9A through 9F are graphs of the photocurrent spectra of the photodetector of FIG. 3 and a reference photodetector at different temperatures and under different biases;

FIG. 10 is a graph of the enhanced factor of the photodetector of FIG. 3 under
20 different biases at 77 K and 293 K obtained from FIGS. 9A through 9F;

FIG. 11 is a graph of the resistance area product of the photodetector of FIG. 3 under different biases at 77 K and 293 K; and

FIGS. 12A through 12D are graphs showing room temperature performance of the
25 photodetector of FIG. 3 and the reference photodetector.

Detailed Description of Exemplary Embodiments

The detailed description set forth below in connection with the appended drawings is intended as a description of presently preferred embodiments of the invention, and is not intended to represent the only forms in which the present invention may be practiced. It is
5 to be understood that the same or equivalent functions may be accomplished by different embodiments that are intended to be encompassed within the scope of the invention.

Referring now to FIG. 1, a photodetector 10 is shown. The photodetector 10 includes a substrate 12, a p-type semiconductor region 14 on the substrate 12, an intrinsic semiconductor region 16 on the p-type semiconductor region 14, an n-type semiconductor
10 region 18 on the intrinsic semiconductor region 16, a surface plasmonic structure 20 on the n-type semiconductor region 18, a cathode 22 electrically connected to the n-type semiconductor region 18, and an anode 24 electrically connected to the p-type semiconductor region 14.

In the embodiment shown, one or more buffer layers 26 are provided between the
15 substrate 12 and the p-type semiconductor region 14 and a passivation layer 28 is provided over the substrate 12, the p-type semiconductor region 14, the intrinsic semiconductor region 16 and the n-type semiconductor region 18.

In the present embodiment, the photodetector 10 is an *n-i-p* photodiode enhanced by surface plasmon polaritons (SPPs) through the integration of the surface plasmonic
20 structure 20. The SPP enhancement may be monitored by monitoring the bias to the photodetector 10. The photodetector 10 may be operable at room temperature and may be configured to receive incident mid-wave infrared radiation 30. The photodetector 10 may be formed into a square or circular mesa and the square or circular mesa may have a size of between about 5 microns (μm) and about 600 μm , more preferably, between about 10 μm
25 and about 600 μm , and, most preferably, between about 40 μm and about 600 μm .

The substrate 12 may be an n-type substrate such as, for example, a gallium antimonide (GaSb) substrate. Advantageously, selection of an n-type substrate reduces optical absorption caused by p-type doping in case the photodetector 10 is used through backside illumination.

In the present embodiment, the intrinsic semiconductor region 16 may include an indium arsenide antimonide (InAsSb) layer. Advantageously, large size and uniform InAsSb-based materials are easy to grow, which is advantageous for large area array. In one embodiment, the InAsSb layer may include $\text{InAs}_{0.912}\text{Sb}_{0.088}$. In such an embodiment, the component of Sb in the active absorption InAsSb layer is 0.088 corresponding to a responding wavelength range of 3 μm to 5 μm with a cut-off wavelength at around 5 μm at room temperature. Thus, the response of the photodetector 10 can cover the important atmospheric window of 3 μm to 5 μm . The InAsSb layer may have a thickness T_i of between about 0.1 micron (μm) and about 5 μm , more preferably, between about 1 μm and about 2 μm . In one embodiment, the thickness T_i of the intrinsic InAsSb layer sandwiched between n-doped and p-doped layers may be about 1.5 μm to balance transit time of carriers or response speed and gain. Further advantageously, such a thickness provides a maximum overlap with the penetration depth of the SPPs to achieve optimized enhancement.

The n-type semiconductor region 18 may include a first aluminium indium arsenide antimonide (AlInAsSb) layer 32 on the InAsSb layer 16 and a gallium antimonide (GaSb) layer 34 on the first AlInAsSb layer 32. In one embodiment, the first AlInAsSb layer 32 may include $\text{Al}_{0.15}\text{InAsSb}_{0.091}$. The n-type semiconductor region 18 may have a thickness T_n of between about 20 nanometres (nm) and about 300 nm, more preferably, between about 20 nm and about 100 nm. In one embodiment, the thickness T_n of the n-doped AlInAsSb and GaSb layers 32 and 34 between the active intrinsic InAsSb layer 16 and the surface plasmonic structure 20 may be reduced to only about 70 nm to reduce damping of the SPPs and form the *n* side layer in the *n-i-p* configuration. In the same or a different embodiment, the first AlInAsSb layer 32 may have a thickness T_{n1} of between about 10 nanometres (nm) and about 150 nm, more preferably, between about 20 nm and about 40 nm, and the GaSb layer 34 may have a thickness T_{n2} of between about 10 nanometres (nm) and about 150 nm, more preferably, between about 30 nm and about 60 nm. In one embodiment, the thickness T_{n1} of the first AlInAsSb layer 32 may be about 20 nm and the thickness T_{n2} of the n-type GaSb layer 24 may be about 50 nm to maximize access of the excited SPPs to the active intrinsic absorption layer 16 and to form the N-type ohmic contact.

The p-type semiconductor region 14 may include an aluminium gallium antimonide (AlGaSb) layer 36 and a second aluminium indium arsenide antimonide (AlInAsSb) layer 38

between the AlGaSb layer 36 and the InAsSb layer 16. In one embodiment, the AlGaSb layer 36 may include one or more sub-layers with an aluminium (Al) component of from about 10 % to about 42%. In the same or a different embodiment, the AlGaSb layer 36 may include $\text{Al}_{0.42}\text{Ga}_{0.58}\text{Sb}$ and the second AlInAsSb layer 38 may include $\text{Al}_{0.2}\text{In}_{0.8}\text{As}_{0.912}\text{Sb}_{0.088}$.

5 Advantageously, insertion of a p-doped $\text{Al}_{0.2}\text{In}_{0.8}\text{As}_{0.912}\text{Sb}_{0.088}$ layer 38 between $\text{Al}_{0.42}\text{Ga}_{0.58}\text{Sb}$ and $\text{InAs}_{0.912}\text{Sb}_{0.088}$ limits type II electron-hole transitions at this interface. Further advantageously, utilisation of a p-doped $\text{Al}_{0.42}\text{Ga}_{0.58}\text{Sb}$ layer 36, a p-doped $\text{In}_{0.8}\text{Al}_{0.2}\text{As}_{0.912}\text{Sb}_{0.088}$ layer 38 and an n-doped $\text{Al}_{0.15}\text{InAsSb}_{0.091}$ layer 32 helps reduce dark current.

10 The passivation layer 28 serves to reduce leakage current and protect the mesa. The passivation layer 28 may be formed of silicon dioxide (SiO_2) or silicon nitride (Si_3N_4) and may have a thickness T_{pl} of between about 200 nanometres (nm) and about 600 nm. In one embodiment, the passivation layer 28 has a thickness T_{pl} of about 300 nm.

In the embodiment shown, the surface plasmonic structure 20 is integrated or
15 arranged on top of the *n-i-p* structure to enhance photodetection. The surface plasmonic structure 20 may include a two-dimensional subwavelength hole array (2DSHA).

Referring now to FIGS. 2A and 2B, a two-dimensional subwavelength hole array (2DSHA) surface plasmonic structure 50 is shown. The 2DSHA 50 may be formed of a plurality of perforations or holes 52 in a metallic material 54. The holes 52 of the 2DSHA 50
20 may have a period p of between about 500 nm and about 1600 nm in both x- and y-directions. The optimal period p of the 2DSHA 50 may be set to about 900 nm in one embodiment to provide SPP resonance at 3.5 μm located at around peak responsivity of the photodetector 10. The holes 52 may have a size d of about half the period p of the holes 52. The surface plasmonic structure 50 may have a thickness t of greater than a skin depth
25 of received radiation to avoid direct transmission through the metal film. The skin depth of the radiation may be calculated using equation (1) below:

$$\delta_s = \sqrt{\rho / (\pi f \mu)} \quad (1)$$

where ρ represents resistivity, f represents frequency and μ represents relative permeability. In one embodiment, the total thickness t of the surface plasmonic structure 50
30 may be about 73 nm including a 3 nm thick titanium (Ti) adhesion layer and a 70 nm thick

gold (Au) layer. In one embodiment, the surface plasmonic structure 50 may have a length L of about 220 μm and a width W of about 220 μm .

Example

Referring now to FIG. 3, a large area scanning electron microscope (SEM) image taken from the top of a photodetector formed in accordance with an embodiment of the present invention is shown. A 2D SHA area 100, a metal contact 102 and passivation areas 104 can be seen from FIG. 3. Both the *n-i-p* photodiode and the 2D SHA are designed by considering optimized interaction between the two.

The *n-i-p* structure was grown by molecular beam epitaxy (MBE) and details of the structural parameters of the *n-i-p* structure are provided in Table 1 below.

Table 1

Layer	Material and Doping	Concentration	Thickness
N-type layer 1	GaSb	$n \sim 2 \times 10^{18} \text{ cm}^{-3}$	$\sim 50 \text{ nm}$
N-type layer 2	$\text{Al}_{0.15}\text{InAsSb}_{0.091}$	$n \sim 2 \times 10^{18} \text{ cm}^{-3}$	$\sim 20 \text{ nm}$
Intrinsic layer	$\text{InAs}_{0.912}\text{Sb}_{0.088}$		$\sim 1500 \text{ nm}$
P-type layer	$\text{Al}_{0.2}\text{In}_{0.8}\text{As}_{0.912}\text{Sb}_{0.088}$	$p \sim 2 \times 10^{18} \text{ cm}^{-3}$	$\sim 20 \text{ nm}$
P-type barrier and gradual layers 1	$\text{Al}_{0.42}\text{Ga}_{0.58}\text{Sb}$	$p \sim 2 \times 10^{18} \text{ cm}^{-3}$	$\sim 40 \text{ nm}$
P-type barrier and gradual layers 2	AlGaSb:BeAl from 10% to 42%	$p \sim 2 \times 10^{18} \text{ cm}^{-3}$	$\sim 30 \text{ nm}$
Buffer layers	GaSb:Be	$p \sim 2 \times 10^{18} \text{ cm}^{-3}$	$\sim 1000 \text{ nm}$
Substrate	GaSb		

The top and bottom ohmic contacts are 15 nm thick titanium (Ti) followed by 200 nm thick gold (Au). The 300 μm sized square or circular mesas are then defined by wet or dry etching, followed by deposition of 300 nm of SiO_2 passivation layers via plasma-enhanced chemical vapor deposition (PECVD) to reduce leakage current and protect the mesas. The metallic 2D SHA structure was fabricated on top of the *n-i-p* mesa by electron beam lithography (EBL), followed by metal evaporation and a standard lift-off process.

Referring now to FIGS. 4A through 4D, scanning electron microscope (SEM) images of two-dimensional subwavelength hole array (2DSHA) surface plasmonic structures with different periods are shown. More particularly, FIG. 4A is an SEM image of a 2DSHA surface plasmonic structure having a period of 550 nm in both x- and y- directions, FIG. 4B is an SEM image of a 2DSHA surface plasmonic structure having a period of 900 nm in both x- and y- directions, FIG. 4C is an SEM image of a 2DSHA surface plasmonic structure having a period of 1280 nm in both x- and y- directions and FIG. 4D is an SEM image of a 2DSHA surface plasmonic structure having a period of 1550 nm in both x- and y- directions. The sizes of the square holes are half of the respective periods.

Referring now to FIG. 5, a graph of the penetration depth of surface plasmon resonance (SPR) in the photodetector is shown and a corresponding theoretical analysis is described below.

For a gold (Au) film integrated on top of the n-type GaSb with a hole period p , the SPR wavelengths λ_{ij} at the 2DSHA/semiconductor interface are calculated by equation (2)

below:

$$\lambda_{ij} = \frac{p}{\sqrt{i^2 + j^2}} \operatorname{Re} \left\{ \left[\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d} \right]^{1/2} \right\} \quad (2)$$

where (i, j) represent a set of integers denoting mode orders in the x- and y- directions and ϵ_m (ϵ_d) represent the dielectric constant of the metal (dielectric). The dielectric constant of GaSb in the considered wavelength range is approximately 15.1.

At Medium Wavelength Infrared (MWIR) range, the imaginary part of the permittivity is negligible, while the dielectric constant of gold can be expressed by Drude model and calculated with equation (3) below:

$$\epsilon_m(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\omega_\tau)} \quad (3)$$

with $\epsilon_\infty = 1$ as the high frequency dielectric constant, $\omega_p = 1.37 \times 10^{16}$ rad/s as the plasma frequency and $\omega_\tau = 4.07 \times 10^{13}$ rad/s as the collision frequency.

Combining equations (2) and (3), for the 2DSHA metallic structure with $p = 900$ nm, the SPR wavelengths can be deduced as approximately $3.5 \mu\text{m}$ for the fundamental plasmonic mode.

On the other hand, the penetration depth of the SPP evanescent fields in the dielectric can be calculated with equation (4) below:

$$\delta_d = \frac{1}{k_0} \left| \frac{\epsilon'_m + \epsilon_d}{\epsilon_d^2} \right|^{\frac{1}{2}} \quad (4)$$

where ϵ'_m represents the real part of the permittivity for gold.

Thus, the penetration depth of the SPR at $3\text{-}5 \mu\text{m}$ can be calculated to be about $1.5 \mu\text{m}$ as shown in FIG. 5, which offers best overlapping with the intrinsic InAsSb layer. The confinement of SPPs in a finite depth can largely enhance the optical electrical field in the semiconductor (confine light), which can result in significant enhancement of light-matter interaction. Therefore, much higher absorption and generating of electron hole pairs can lead to a largely enhanced photocurrent. In turn, improved responsivity and sensitivity can be achieved with thinner absorption layers that will not sacrifice response speed of the photodiode.

With reference to FIGS. 6A through 8, photocurrent enhancement of the 2DSHA $n\text{-}i\text{-}p$ photodiode at zero bias will now be discussed. The photocurrent spectra of the 2DSHA $n\text{-}i\text{-}p$ devices with different hole periods are presented both at 293 K (room temperature) and 77 K. FIGS. 6A through 6D show photocurrent spectra of 2DSHA $n\text{-}i\text{-}p$ photodiodes with different periods ((a) $p = 900$ nm, (b) $p = 550$ nm, (c) $p = 1280$ nm and (d) $p = 1550$ nm, respectively) and an $n\text{-}i\text{-}p$ reference device without 2DSHA under zero bias at room temperature. FIGS. 7A through 7D show photocurrent spectra of 2DSHA $n\text{-}i\text{-}p$ photodiodes with different periods ((a) $p = 900$ nm, (b) $p = 550$ nm, (c) $p = 1280$ nm and (d) $p = 1550$ nm, respectively) and an $n\text{-}i\text{-}p$ reference device without 2DSHA under zero bias at 77 K. FIG. 8 shows the relative spectral response of the InAsSb $n\text{-}i\text{-}p$ photodiode under zero bias at 77 K and 293 K, respectively.

In each of FIGS. 6 and 7, the photocurrent spectra of the *n-i-p* reference device are first presented over the wavelength range 2 μm to 6 μm at both 77 K and 293 K (room temperature). As shown in FIG. 8, the InAsSb based *n-i-p* photodiode has broadband response from 1.8 μm to 5 μm at 293 K. The relative spectral responsivity possesses a
5 cutoff wavelength at approximately 4.8 μm at 293 K and shows a shift to approximately 4.2 μm at 77 K.

The 2DSHA *n-i-p* device with $p = 900$ nm shows a significant photocurrent enhancement at both 293 K and 77 K. It offers about approximately 3 times photocurrent enhancement under zero bias. The 2DSHA devices with other periods also show
10 approximately 50% to 100% photocurrent enhancement. Therefore, the experimental results show that using a metallic 2DSHA structure with properly designed hole-period can largely enhance photocurrent of the InAsSb based *n-i-p* photodiode by a factor of approximately 3 times at zero bias.

With reference to FIGS. 9A through 11, electronic control of the enhancement will
15 now be discussed. The performance of *n-i-p* devices can be modulated by changing the operational temperature and bias voltage. Therefore, it can be reasonable that these two factors would also have some effects on the enhancement contribution of the metallic 2DSHA.

FIGS. 9A through 9F show the effects of temperature and bias voltage on
20 performance of the 2DSHA *n-i-p* detectors and the reference *n-i-p* detector. More particularly, FIG. 9A shows the photocurrent spectra of the reference *n-i-p* detector at different temperatures under zero bias, FIG. 9B shows the photocurrent spectra of the 2DSHA *n-i-p* detector at different temperatures under zero bias, FIG. 9C shows the photocurrent spectra of the reference *n-i-p* detector under different bias at 293 K, FIG. 9D shows the photocurrent
25 spectra of the 2DSHA *n-i-p* detector under different bias at 293 K, FIG. 9E shows the photocurrent spectra of the reference *n-i-p* detector under different bias at 77 K and FIG. 9F shows the photocurrent spectra of the 2DSHA *n-i-p* detector under different bias at 77 K. The arrows in FIGS. 9C through 9F indicate the voltage biases.

FIGS. 9A and 9B show the photocurrent spectra of the reference *n-i-p* detector and
30 the 2DSHA *n-i-p* detector at different temperatures under zero bias. As predicted, both detectors show a shift of cut-off wavelengths with decreasing temperature owing to

enlarging of the band-gap energy of the intrinsic InAsSb absorption layers. Additionally, the 2DSHA *n-i-p* detector shows large photocurrent enhancement of approximately 3 to 4 times compared to the reference *n-i-p* detector at every measured temperature.

Referring now to FIGS. 10 and 11, the enhanced factor of the 2DSHA *n-i-p* detector at 3.5 μm under different biases at 293 K and 77 K obtained from FIG. 9 is shown in FIG. 10 and resistance area (RA) product of the 2DSHA *n-i-p* detector under different bias at 293K and 77K is shown in FIG. 11.

As presented, electrical control of enhancement is observed. The photocurrent enhanced factor for the 2DSHA *n-i-p* detector will reach a minimum of approximately 1 at large forward bias both at 293 K and 77 K. This means that no absolute photocurrent enhancement exists under large forward bias. The room temperature enhanced factor shows a maximum of approximately 5 at a slight reverse bias of approximately -150 millivolt (mV). Rather differently, at 77 K, the photocurrent shows the largest enhancement under approximately 50 mV forward bias with an enhanced factor of approximately 6. Such a qualitative difference is also reflected in the RA product shown in FIG. 11, where the largest RA product occurs at -150 mV (for 293 K) and 50 mV (for 77K).

With reference to FIGS. 12A through 12D, performance of the photodetector will now be discussed.

For performance characterization, a 700 degrees Celsius ($^{\circ}\text{C}$) blackbody radiation source was used to characterize the responsivity and detectivity of the 2DSHA-hetero *n-i-p* photodetector with $p = 900 \text{ nm}$ and the reference at room temperature under biased voltages from -350 mV to 350 mV. The room temperature responsivities ($R_i = I_s/P$, where I_s represents the signal current and P represents incident radiation power on a detector calibrated by a standard power meter (OPHIR PHOTONICS)) of the two devices are presented in FIG. 12A. In particular, FIG. 12A show responsivity under biased voltages from -350 mV to 350 mV at room temperature and the inset of FIG. 12A shows room temperature current-voltage characteristics of the photodiodes. It was found that the responsivity of the 2DSHA-hetero *n-i-p* photodetector increases when the biased voltage varies from positive to negative and tends to saturate at about -150 mV with a value of 0.85 amperes per watt (A/W), as compared to 0.15 A/W for the reference at the same bias. It was noted that the responsivity of the reference device is saturated at around -350 mV with

a value of only 0.3 A/W, while that of the plasmonic device saturated at about -150 mV with a much larger value. As the current-voltage curves shown in the inset of FIG. 12A confirm that the plasmonic and reference devices have similar dark current characteristics, the difference in the saturation voltages of the responsivities is primarily due to the plasmonic effect. In the 2DSHA *n-i-p* device, most electron hole pairs (EHPs) are mainly generated in the absorbing layer near the metal-semiconductor interface and the electrons can be fast collected by the electrode. This will lead to a lower bias voltage for the electrons to reach the saturated drift velocity as $u = \mu E$.

Referring now to FIG. 12B, the room temperature blackbody detectivity ($D = R_i / \sqrt{2qJ + 4kT / (RA)}$, where q represents the electronic charge, J represents the dark current density, R represents the dynamic resistance, A represents the area and R_i represents the photocurrent responsivity) of the 2DSHA-hetero *n-i-p* photodetector is $0.80 \times 10^{10} \text{ cm Hz}^{1/2} \text{ W}^{-1}$ at -150 mV as shown in FIG. 12B, compared to $0.12 \times 10^{10} \text{ cm Hz}^{1/2} \text{ W}^{-1}$ of the reference under the same bias voltage, which corresponds to 6.6 times enhancement.

Referring now to FIG. 12C, the external quantum efficiencies (EQE) ($\eta_E = R_i hc / (\lambda q)$, where h represents the Planck constant, c represents the speed of light in vacuum, q represents the element charge, and λ represents the wavelength) at 3.5 μm are presented in FIG. 12C with a maximum value of 30% occurring at -150 mV, corresponding to about 5 times enhancement. It was noted that the EQE for the reference device was only approximately 2% at zero bias, which may be due to the barriers in the hetero *n-i-p* structure.

Referring now to FIG. 12D, impulse responses are shown. The line widths of the impulse responses of the 2DSHA-hetero *n-i-p* device and the reference at zero bias were measured with a 4.77 μm quantum cascade laser (QCL) pulse (200 ns in width). As can be seen from FIG. 12D, the line widths are 600 nanoseconds (ns) for both devices, demonstrating a fast response to the input signal. These measured results show that the performance of the 2DSHA-hetero *n-i-p* photodetector can be significantly improved without sacrificing speed.

As is evident from the foregoing discussion, the present invention provides a photodetector with improved performance. In particular, the present invention provides a surface plasmon polariton (SPP)-enhanced room temperature mid-wave infrared photodetector. Advantageously, the photodetector of the present invention shows
5 significant performance enhancement for low and room-temperature operation. A largely improved blackbody detectivity of about approximately $0.8 \times 10^{10} \text{ cmHz}^{1/2} \text{ W}^{-1}$ is obtained at room temperature, which is much better than those of commercially available products operating at room temperature. Furthermore, even under zero bias at room temperature, the photodetector of the present invention possesses blackbody detectivity of approximately
10 $0.3 \times 10^{10} \text{ cmHz}^{1/2} \text{ W}^{-1}$ and offers largest room temperature detectivity at a very small reverse bias of 150 mV. Advantageously, this significantly reduces the power consumption for external electrical circuits in real applications. Additionally, by changing the bias, the overlap between SPPs and the active absorption layers can be modulated so as to increase the enhancement. As a further advantage, the dark current of the photodetector can be
15 reduced due to the heterojunction *n-i-p* design.

The photodetector of the present invention may be used in a broad range of applications. For example, the photodetector of the present invention can be used as a detector element at mid-infrared wavelength in spectrometers. The photodetector of the present invention can also be used in thermal night-vision imaging as infrared radiation
20 emitted, reflected or transmitted from objectives will take the place of visible radiation as the main electromagnetic waves in such situations. This is of great potential in military applications such as missile guidance, target detective. Furthermore, because the spectral response range of the photodetector of the present invention can cover some characteristic spectral lines of gases, for example, the absorption peak of carbon dioxide (CO_2) at
25 approximately $4.3 \text{ }\mu\text{m}$, it can also be used to analyse the component of gases. The photodetector of the present invention can also be fabricated into linear or large focal planar arrays that can be used as high sensitive cameras for meteorology, astronomy and space exploration.

While preferred embodiments of the invention have been illustrated and described, it
30 will be clear that the invention is not limited to the described embodiments only. Numerous modifications, changes, variations, substitutions and equivalents will be apparent to those

skilled in the art without departing from the scope of the invention as described in the claims.

Further, unless the context clearly requires otherwise, throughout the description and the claims, the words "comprise", "comprising" and the like are to be construed in an
5 inclusive as opposed to an exclusive or exhaustive sense; that is to say, in the sense of "including, but not limited to".

CLAIMS

1. A photodetector, comprising:
a substrate;
5 a p-type semiconductor region on the substrate;
an intrinsic semiconductor region on the p-type semiconductor region;
an n-type semiconductor region on the intrinsic semiconductor region;
a surface plasmonic structure on the n-type semiconductor region;
a cathode electrically connected to the n-type semiconductor region; and
10 an anode electrically connected to the p-type semiconductor region.
2. The photodetector of claim 1, wherein the intrinsic semiconductor region comprises an indium arsenide antimonide (InAsSb) layer.
- 15 3. The photodetector of claim 2, wherein the InAsSb layer comprises $\text{InAs}_{0.912}\text{Sb}_{0.088}$.
4. The photodetector of claim 2 or 3, wherein the InAsSb layer has a thickness of between about 0.1 micron (μm) and about 5 μm .
- 20 5. The photodetector of any one of claims 2 to 4, wherein the n-type semiconductor region comprises a first aluminium indium arsenide antimonide (AlInAsSb) layer on the InAsSb layer and a gallium antimonide (GaSb) layer on the first AlInAsSb layer.
6. The photodetector of claim 5, wherein the first AlInAsSb layer comprises
25 $\text{Al}_{0.15}\text{InAsSb}_{0.091}$.
7. The photodetector of claim 5 or 6, wherein the n-type semiconductor region has a thickness of between about 20 nanometres (nm) and about 300 nm.
- 30 8. The photodetector of claim 7, wherein the first AlInAsSb layer has a thickness of between about 10 nanometres (nm) and about 150 nm and the GaSb layer has a thickness of between about 10 nanometres (nm) and about 150 nm.

9. The photodetector of any one of claims 2 to 8, wherein the p-type semiconductor region comprises an aluminium gallium antimonide (AlGaSb) layer and a second aluminium indium arsenide antimonide (AlInAsSb) layer between the AlGaSb layer and the InAsSb layer.
- 5 10. The photodetector of claim 9, wherein the AlGaSb layer comprises $\text{Al}_{0.42}\text{Ga}_{0.58}\text{Sb}$ and the second AlInAsSb layer comprises $\text{Al}_{0.2}\text{In}_{0.8}\text{As}_{0.912}\text{Sb}_{0.088}$.
11. The photodetector of claim 9 or 10, wherein the AlGaSb layer comprises one or
10 more sub-layers with an aluminium (Al) component of from about 10 % to about 42%.
12. The photodetector of any one of the preceding claims, wherein the surface plasmonic structure comprises a two-dimensional subwavelength hole array (2DSHA).
- 15 13. The photodetector of claim 12, wherein the 2DSHA comprises a plurality of perforations in a metallic material.
14. The photodetector of claim 12 or 13, wherein a plurality of holes of the 2DSHA has a period of between about 500 nm and about 1600 nm.
- 20 15. The photodetector of claim 14, wherein the period of the holes of the 2DSHA is about 900 nm.
16. The photodetector of claim 14 or 15, wherein the holes have a size of about half the
25 period of the holes.
17. The photodetector of any one of the preceding claims, wherein the surface plasmonic structure has a thickness of greater than a skin depth of received radiation.
- 30 18. The photodetector of any one of the preceding claims, further comprising a passivation layer over the substrate, the p-type semiconductor region, the intrinsic semiconductor region and the n-type semiconductor region.

19. The photodetector of claim 18, wherein the passivation layer has a thickness of between about 200 nanometres (nm) and about 600 nm.

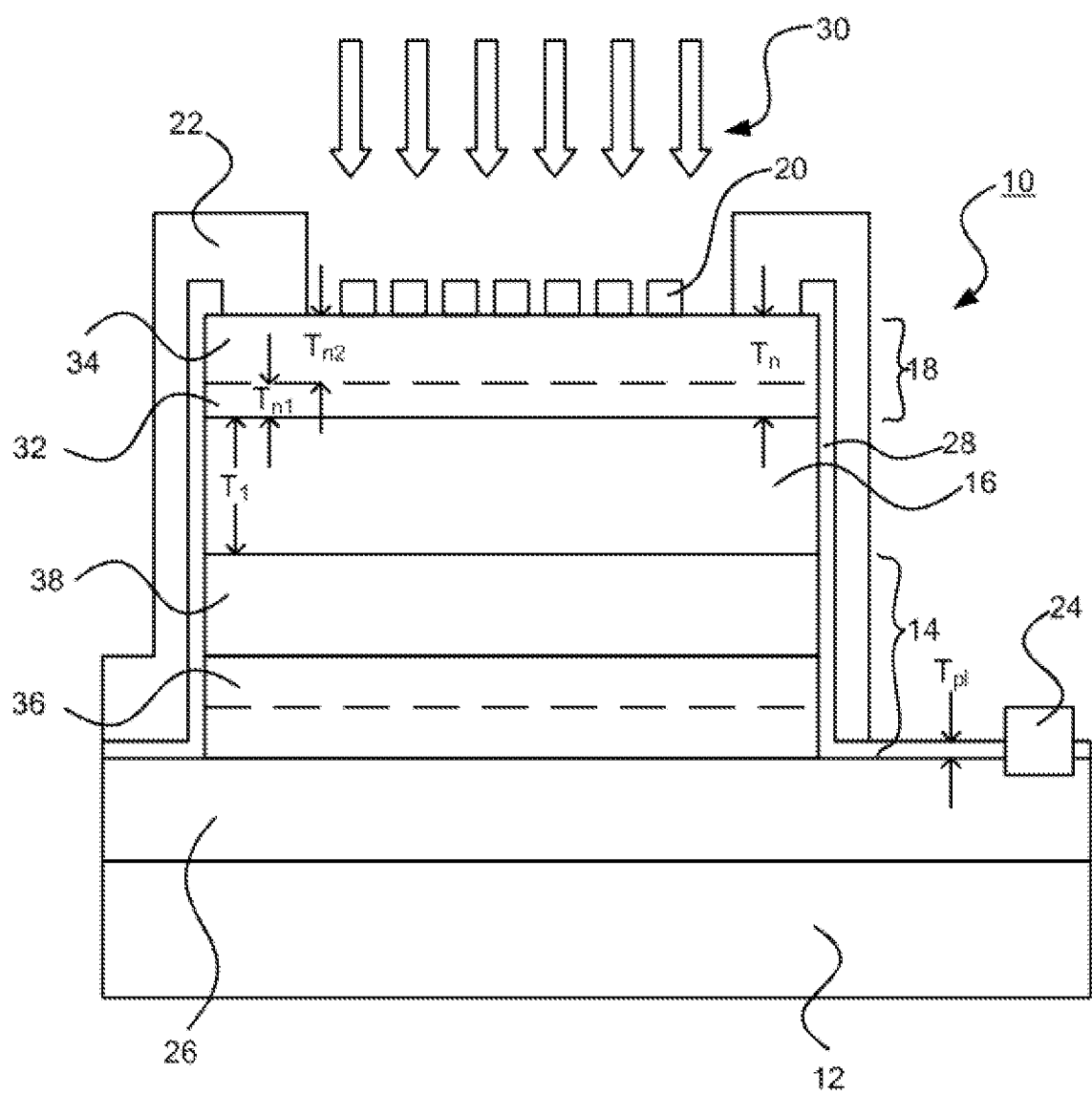


FIG. 1

2/10

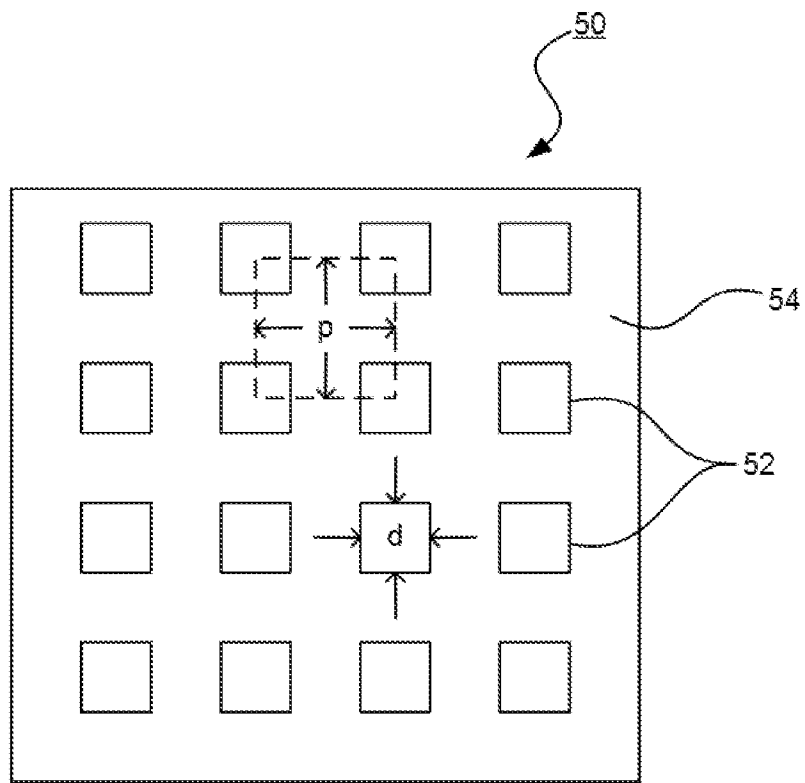
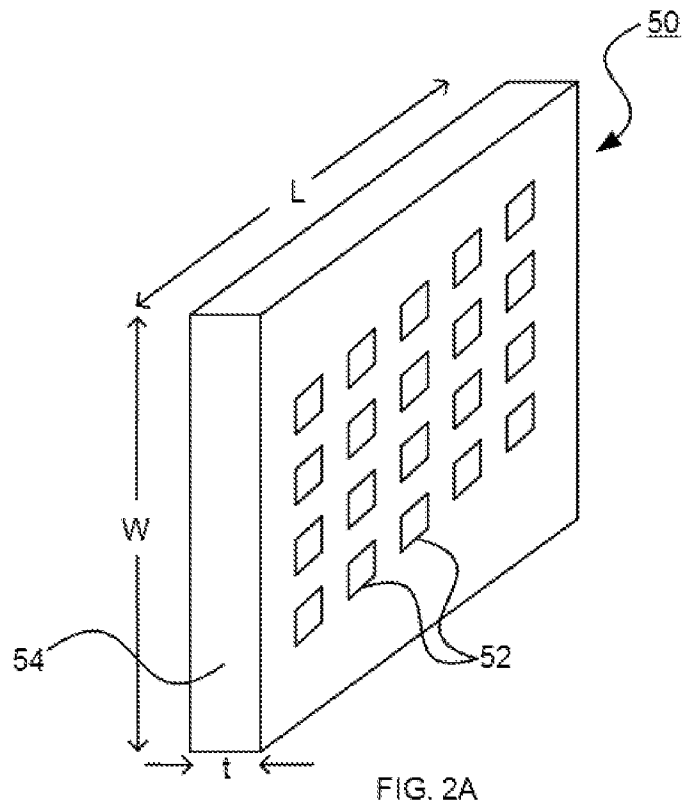


FIG. 2B

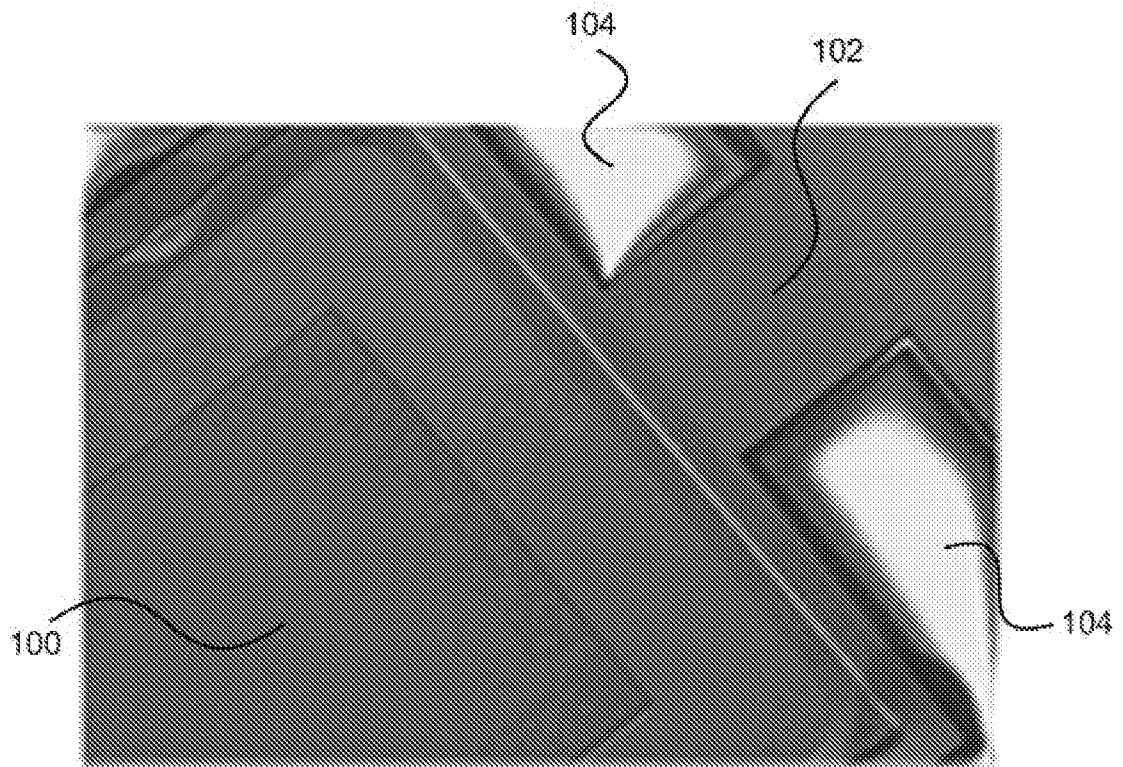


FIG. 3

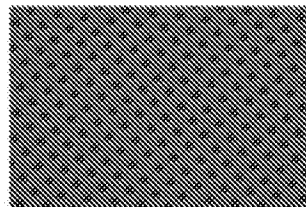


FIG. 4A

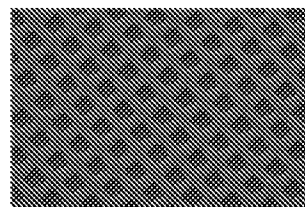


FIG. 4B

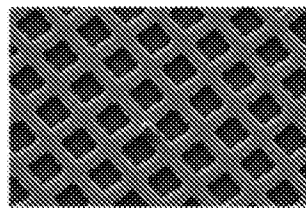


FIG. 4C

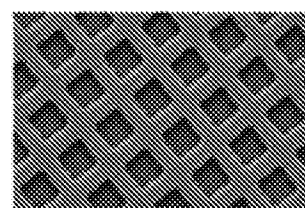


FIG. 4D

4/10

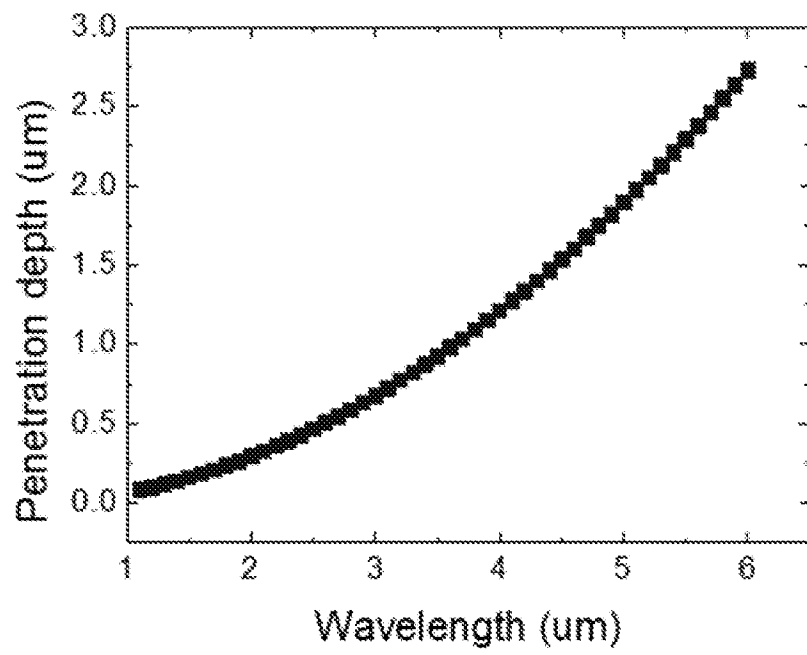


FIG. 5

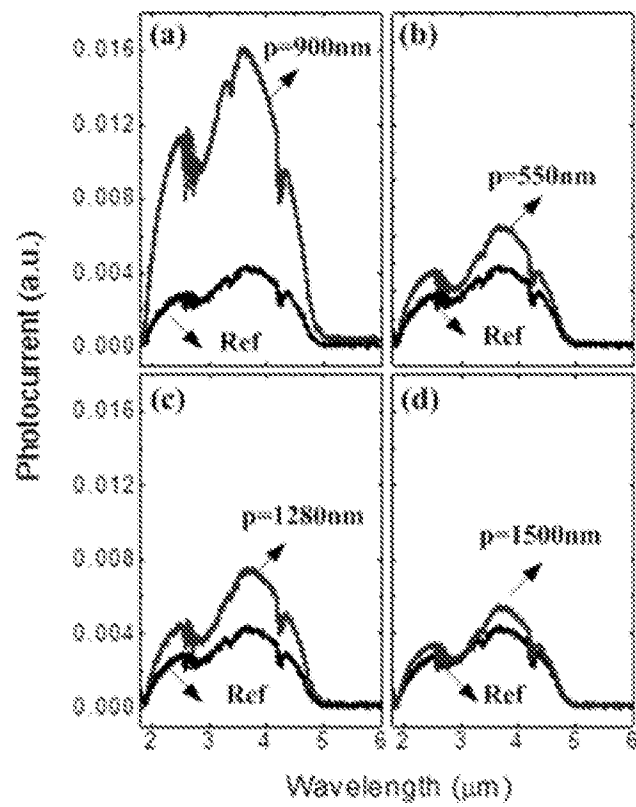


FIG. 6

5/10

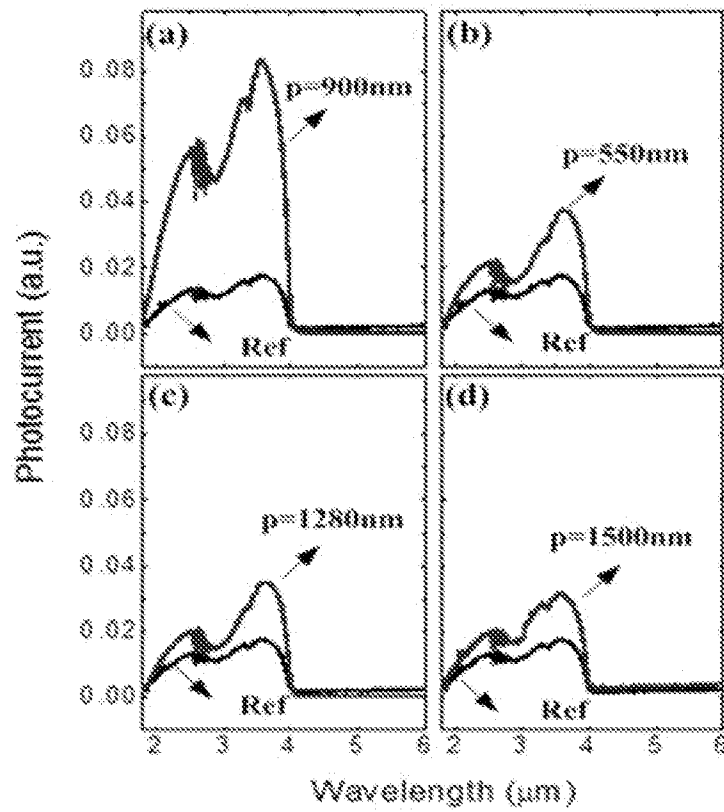


FIG. 7

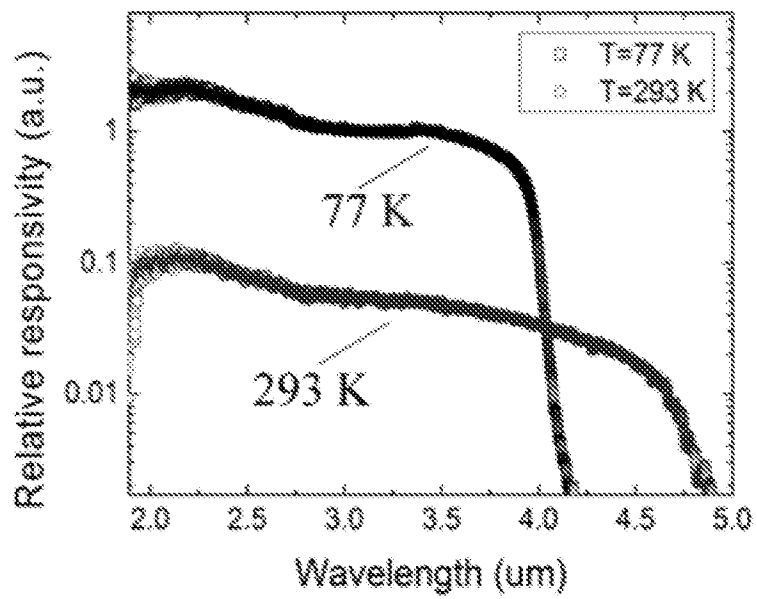


FIG. 8

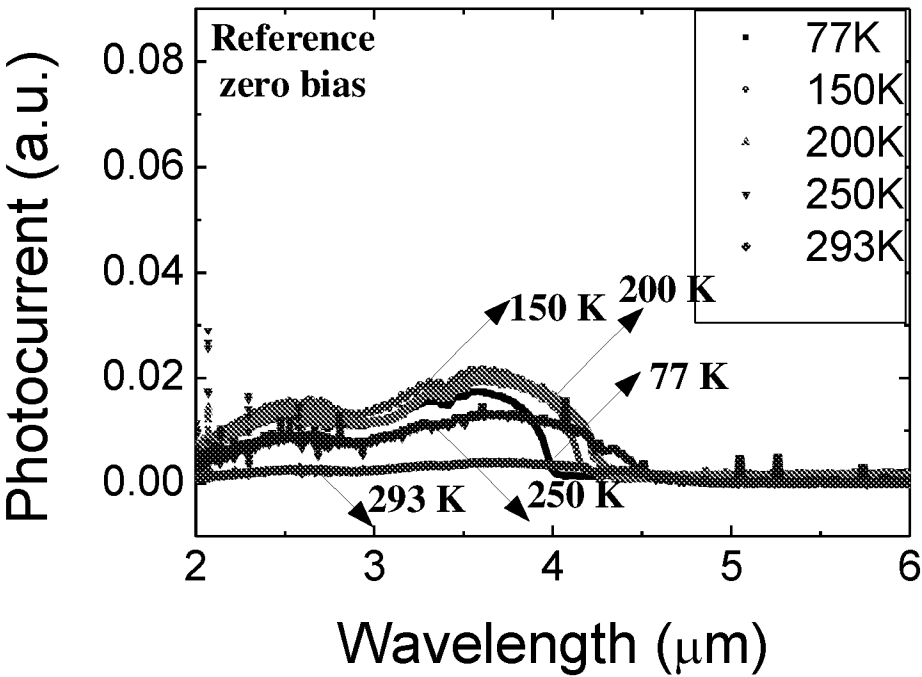


FIG. 9A

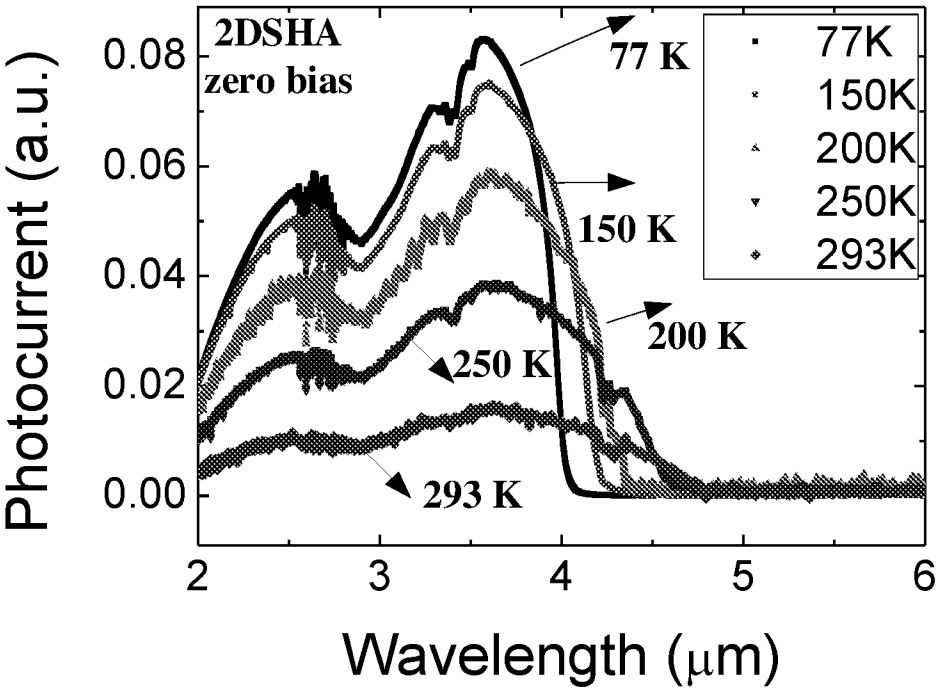


FIG. 9B

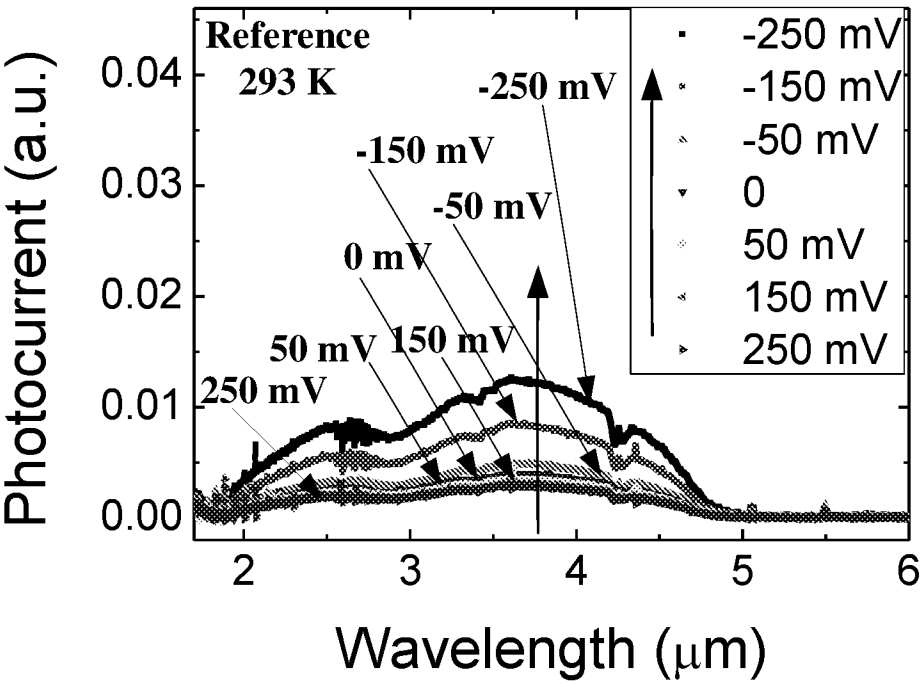


FIG. 9C

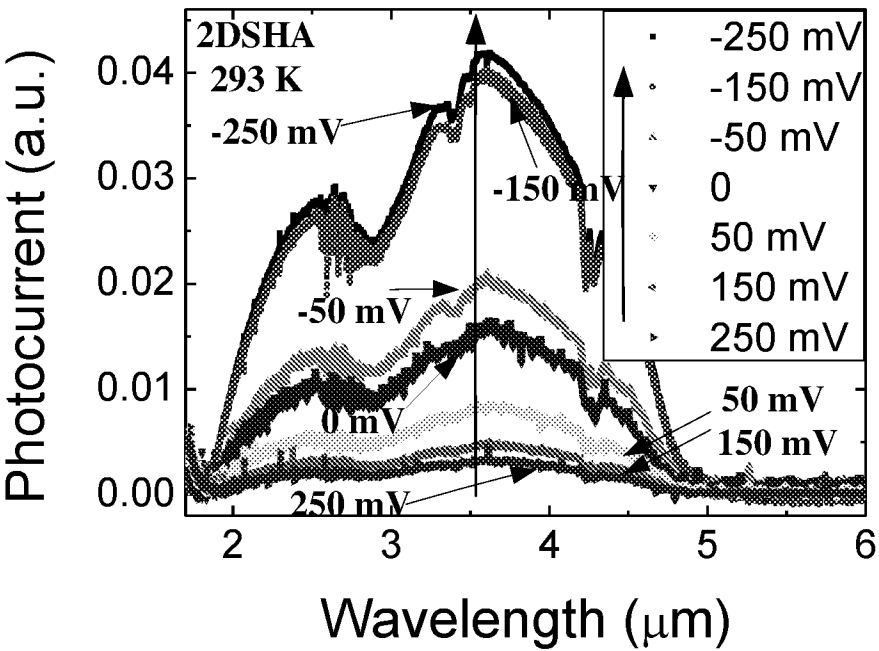


FIG. 9D

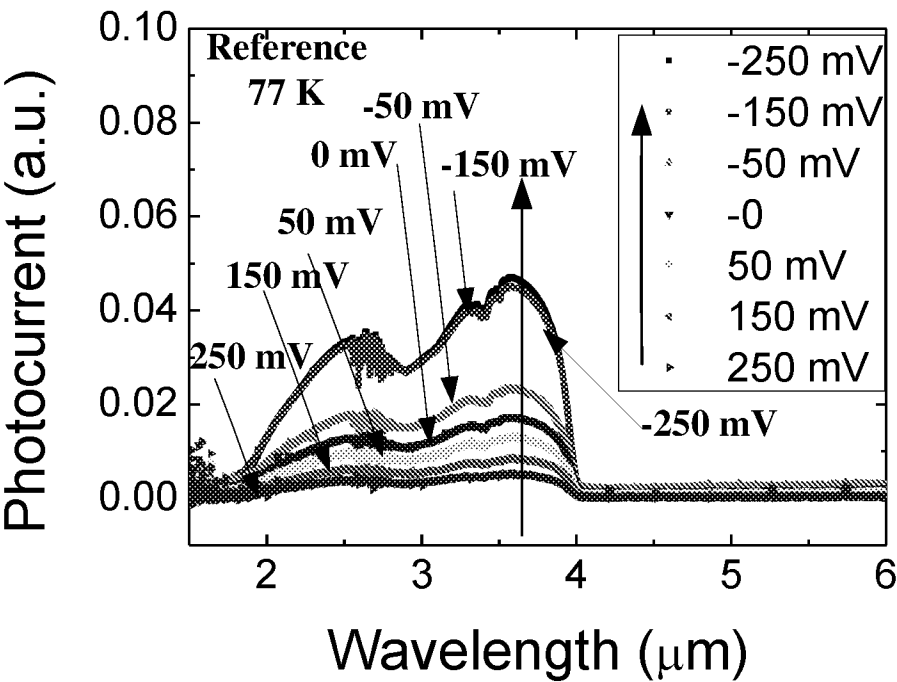


FIG. 9E

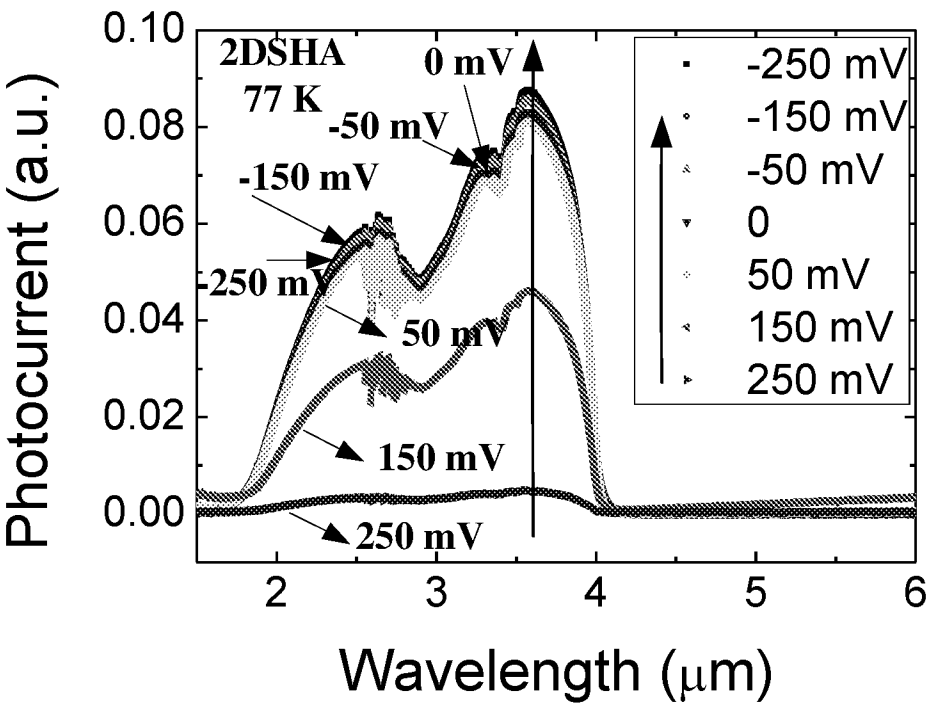


FIG. 9F

9/10

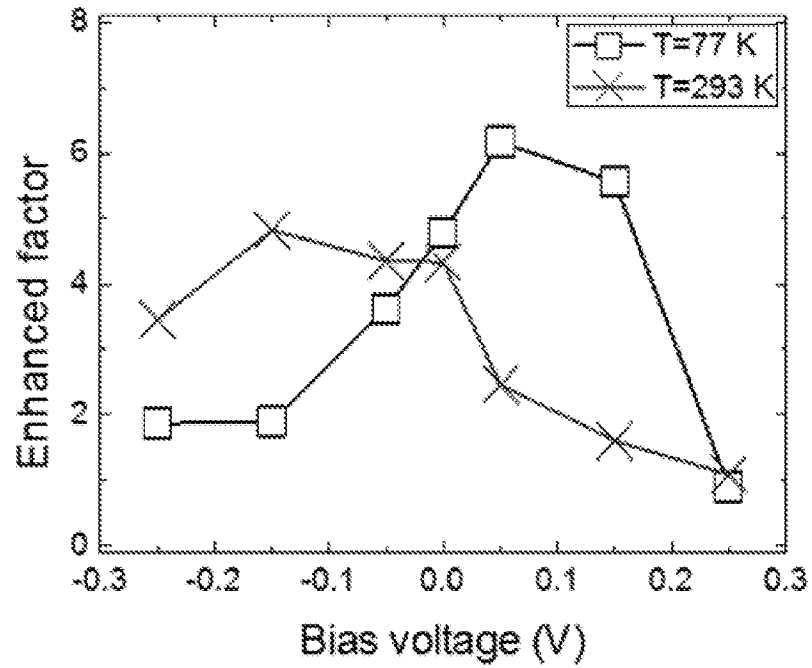


FIG. 10

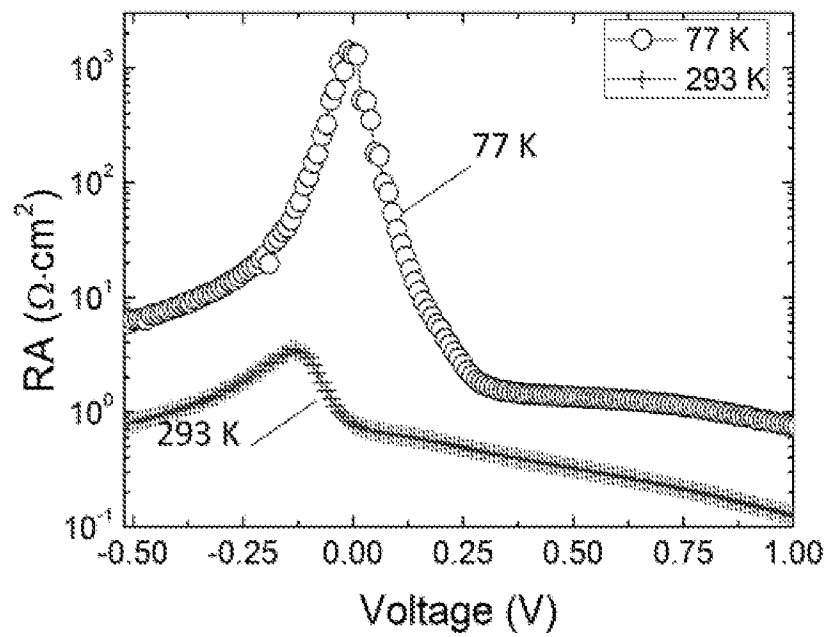


FIG. 11

10/10

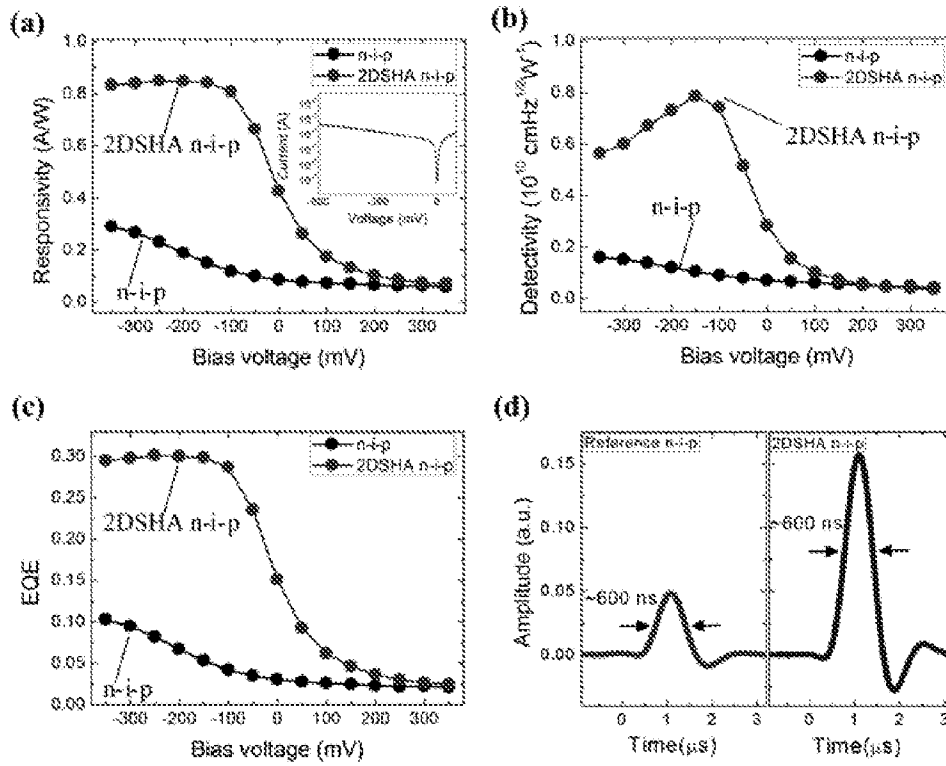


FIG. 12