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Optical Modelling Of Gaas/Gasb Core-Shell Cone Topped Octagonal Faced Nanopillar Array With Periodic Trapezoidal Textured Cut For High Photon Trapping Efficiency

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Abstract:

Proficiency in light reflectance mitigation is the most crucial factor for high photodetector performance. In this respect light trapping mechanism based on nanostructures or microstructures such as nanopillars, nanocones, nanopyramids have emerged as the most promising candidate for reducing overall light reflectance. This could be attributed to its effective large irradiation area, multiple scattering of incident light as well as increased path length of incident rays in these nanostructures. This paper proposes an optical modelling of a GaAs/GaSb material based vertically oriented core-shell cone topped octagonal shaped nanopillar structure with periodical trapezoidal nanotexturization over it to be deployed over a circular planar detector's surface of radius 50 μ m. The geometrical analytical investigation of the proposed model exhibits a 0.999 overall absorbance and 0.995 A/W photoresponsivity along with 87% EQE at 1 μ m operating wavelength.

Index Terms—external quantum efficiency, nanopillar, photoresponsivity, reflectance, trapezoidal textured cut.

I. Introduction

The photodetector performance efficiency greatly depends upon the probability of optimum photon absorption as well as efficiency in carrier collection[1,2]. Vertical nanopillars are emerged as the most promising candidate in attaining high light absorbance efficiency. This could be attributed to their unique light trapping mechanism through specular reflectance[3]. The proper tailoring of the nanopillar structural parameters such as diameter, length as well as pitch scale length brings tremendous enhancement in the light absorption efficiency[4,5]. In order to promote further enhancement in the light absorbance efficiency, textured nanostructures exhibit supreme optical effects through multiple light scattering phenomenon. A few includes: single-layer GaAs based nano pyramids which have been prepared through a combination of lithography, metal enhanced chemical vapour deposition method and gas-phase substrate provides remarkable absorption at wider radiation spectrum and the broad ranging incident angle at large curvature bending[6]. A 2 μm thick i NPW arrays coated with 40 nm silicon layer provides an integrated absorption of approx 89%[7]. Surface texturing of silicon with oblique nanopillars reduces light reflection lesser than 10%[8]. Besides attaining optimum light absorbance, light collection efficiency is another significant factor that decides the proficiency of the photodetector performance. In this pursuit thin films have been previously adopted for achieving a good carrier collection efficiency[9]. However, the film thickness emerge to be of critical dimension. Exciton pairs which are generated greater than one diffusion length away from the pn junction space region produces a vanishing probability of carrier efficiency[10]. Also they consist of high density recombination sites[11]. This constraint is overcome by the core-shell nanopillar structure. Core-shell p-n junction embedded within the nanopillar structure allows orthogonalization of the photon absorption and carrier collection direction[12,13]. Owing to this the minority carriers travel a shorter path length as compared to the minority diffusion length. Moreover, the outer shell act as a passivating layer for the inner core that could suppress the surface states[14]. Also, these shell layers consisting of high bandgap material prohibits the carrier from recombination at the surface[15].

In the previous work, authors have demonstrated the effect of nano-texturization over vertical nanopillar structures in mitigating total light reflectance phenomenon which includes: GaAs material based nanotextured pyramidal cut nanopillar array[16], InGaAs material based hexagonal nanopillar array [17], right triangular texturized GaAs material based square shaped nanopillar deployed over the front photodetector's surface [18] and half octagonal cut based hexagonal shaped nanopillar array over the light reflectance minimization for high

photodetector's responsivity[19].However, to boost the light absorbance to the next level as well to trap maximum incoming photons the nanopillar structure has been upgraded to octagonal faced.

This work proposes a cone topped GaAs/GaSb core-shell radial junction based octagonal faced nanopillar array with periodic n-trapezoidal cut based texturization over the nanopillar structure to be deployed over a circular shaped detector's planar surface.The conical top over the octagonal faced nanopillar structure has been adopted in order to reduce the effective refractive index of air semiconductor mismatch to a lowest level for the 0^0 incident photons.The structural parameters of the proposed model which includes the trapezoidal pattern based nanotextured cutting angle,optimal interpillar gap of the array as well as the light scattering mechanism within the proposed structure have been analytically investigated and modelled accordingly so as to trap the maximum incoming light.

In this paper the authors have proposed a conical topped GaAs/GaSb core-shell radial junction based octagonal faced nanopillar array consisting of periodic n-trapezoidal cut based texturization over the nanopillar structure deployed over a circular shaped detector's planar surface. The conical shape has been attained in order to reduce the effective refractive index of air semiconductor mismatch to a lowest level for the 0^0 incident photons.The structural parameters of the proposed model including the core-shell thickness,trapezoidal textured angle,optimal interpillar spacing of the array as well as the light scattering mechanism within the proposed structure have been analytically investigated and modelled accordingly so as to trap the maximum incoming light. Section II demonstrates the optical modelling of the proposed nanopillar array along with the mathematical analysis of the structural parameters of the proposed structure.Section III depicts the photovoltaic characterization as well as the effect of the proposed nanopillar structural parameters over the photodetector's performance metrics in the form of simulative representations.

II. Optical modelling of the NP array structure

Figure 1 (a) depicts the schematic representation of the proposed GaAs/GaSb material based core-shell cone topped octagonal faced radial p-n homojunction vertical nanopillar array structure over which periodically patterned trapezoidal cut based nanotexturization has been done.The core consist of two layers of p-GaAs and n-GaAs material of radius ' r_1 ' and ' r_2 ' respectively.The GaSb passivation layer

consist of a layer thickness of ' t ' μm . The trapezoidal based nanotextured base lengths are denoted by b_1 and b_2 . ' s ' being the interpillar gap deployed over a circular detector's front surface area of diameter ' D ' . To demonstrate the light reflectance pattern followed within the nanopillar array, geometric ray optics has been adopted. For the analytical investigation, a bunch of five photons operating at 900nm wavelength has been considered to get emitted from a 3mm diameter GaAs LED source.

The benefit of the adopting trapezoidal based nanotextured cut as compared to the previously adopted nanotextures[16,18,19] could be illustrated from Figure.2.

(a)

Fig. 1.(a)3D schematic of the proposed cone mounted GaAs/GaSb core shell based octagonal faced periodic n-trapezoidal cut nanotextured nanopillar array photodetector surface structure over a circular surface area, (b)Cross sectional Schematic of the proposed nanopillar structure representing the homojunction GaAs layers along with the GaSb passivating layer and the trapezoidal textured cut. .

(b)

(c)

Fig.2. Light interaction pattern followed within the interpillar spacing of various nanotextured cut based nanopillar model:(a) pyramidal cut texturization ($\theta_{t1}=\theta_{t2}=30^\circ$), (b) right triangular texturization ($\theta_{t1}=30^\circ, \theta_{t2}=90^\circ$), (c) proposed trapezoidal textured based nanopillar array ($\theta_{t1}=50^\circ, \theta_{t2}=50^\circ, \theta_B=60^\circ$)

The analytical investigation of the light reflectance followed within the proposed cone topped octagonal faced nanopillar model with trapezoidal nanotextures over it

has compared with the previously proposed right triangular nanotextures as well as pyramidal cut textures over the octagonal faced nanopillar structure. For the geometrical ray analysis, two 30° incident incoming photons have been considered to get trapped within the interpillar gap of the nanopillar array.

Figure 2(a) depicts the internal light reflectance patterned followed within the previously proposed periodically arranged pyramidal cut based nanotexture adopted in the now proposed octagonal faced nanopillar array structure. As illustrated in the figure, two of the incident photons are trapped within the interpillar gap of the two nanopillars. First incoming ray (Ph-1) strikes the detector's front surface with an incident angle 30° . After some amount of absorption took place within the device the primary reflected ray undergoes two more internal reflections within the array. This enhances the total optical path length. Similarly, the second incoming photon (Ph-2) strikes the nanopillar interface at point 'a' with a certain angle ' θ_x '. This photon after undergoing only three internal reflections got lost to air without attributing towards enhanced light absorption.

The light reflectance pattern followed within the interpillar gap of the prior proposed right angle texture based octagonal faced nanopillar array has been depicted in Figure 2(b). As evaluated from the figure, this nanopillar structure could provide a larger number of internal multiple reflections to the incoming photons as compared to the previous pyramidal model. The first incoming photon undergoes seven internal reflections increasing the photon absorption path length to a higher level. Similarly, the second incoming photon undergoes six internal reflections within the interpillar spacing which could increase the light absorption efficiency.

Figure 2(c) depicts the light reflectance followed within the proposed cone topped GaAs/GaSb based core shell octagonal faced nanopillar array structure with trapezoidal nanotexture over it. As could be well illustrated from the figure, the first incoming photon undergoes a maximal number of nine internal reflections while the second incoming photon undergoes a maximal of seven internal reflections within the structure before getting lost to air. Thus, it could be well evaluated that the proposed trapezoidal based nanotexture could provide the maximum number of internal reflections to the incoming light that is engulfed within the nanopillar array. This phenomenon of internal reflections could increase the photon absorption

path length to a maximal level which could reduce the incoming signal loss to minimal level.

The enhancement of the optical absorption path length completely depends on the total internal reflections faced by the incoming photons within the proposed nanopillar structure. These internal reflections completely relies on the striking angles of the incoming photons at the nanopillar interfaces as well as their reverting angles over detector's planar surface. Figure 3(a)-(b) depicts these angular parameters of the incident photon over the proposed nanopillar structure. The formation of the incident angle (θ_{p1}) on the trapezoidal textured interface of the nanopillar array structure has been illustrated in Figure 3(a). The trapezoidal textured structural parameters includes: lower cutting angles (θ_{t1} and θ_{t2}) of 50° each while the upper cutting angles (θ_{t3} and θ_{t4}) both consist of 40° each. The upper and lower base lengths of the trapezoid are termed as b_1 and b_2 respectively. The value of the incident angle (θ_{p1}) striking at the lower side of the trapezoidal textured cut of the nanopillar could be deduced as follows:

(a)

(b)

Fig.3. Angular incidence representation of the photon ray at various nanopillar interfaces: (a) Incident angle (θ_{pi}) and reflected angle (θ_{rp1}) formation at first nanopillar interface (b) Revert angle formation of the reflected ray at the planar detector's surface(θ_m)

$$\begin{aligned}
 & \text{In } \triangle BCM, \\
 & \angle B + \angle BCD + \angle M = 180^\circ \\
 & \Rightarrow \angle \theta_{i2} + 90^\circ - \angle 1 + 90^\circ - \angle \theta_i = 180^\circ \\
 & \Rightarrow \angle \theta_{i2} + 90^\circ - \angle \theta_{p1} + 90^\circ - \angle \theta_i = 180^\circ \\
 & \Rightarrow \angle \theta_{p1} = \angle \theta_{i2} - \angle \theta_i
 \end{aligned} \tag{1}$$

The value of the reflected angle (θ_{rp1}) after the incident photon strikes the nanopillar interface could be formulated as:

$$\begin{aligned}
 & \text{In quadrilateral ABCD,} \\
 & \angle A + \angle B + \angle C + \angle D = 360^\circ \\
 & \Rightarrow \angle \theta_{i1} + \angle 3 + \angle 4 + \angle x + \angle 1 + \angle 2 + 180^\circ - \angle \theta_p = 360^\circ \\
 & \Rightarrow \angle \theta_{i1} + \angle \theta_{rp1} + \angle \theta_{rp1} + \angle x + \angle \theta_{p1} + \angle \theta_{p1} + 180^\circ - (90^\circ - \theta_i) = 360^\circ \\
 & \Rightarrow \angle \theta_{i1} + 2\angle \theta_{rp1} + 2\angle \theta_{p1} + 90^\circ - \angle \theta_{rp1} + 90^\circ - \angle \theta_i = 360^\circ \\
 & \Rightarrow \angle \theta_{i1} + \angle \theta_{rp1} + 2(\angle \theta_{i2} - \angle \theta_i) + 90^\circ + 90^\circ - \angle \theta_i = 360^\circ \\
 & \Rightarrow \angle \theta_{i1} + \angle \theta_{rp1} + 2\angle \theta_{i2} - 2\angle \theta_i + 180^\circ - \angle \theta_i = 360^\circ \\
 & \Rightarrow \angle \theta_{i1} + \angle \theta_{rp1} + 2\angle \theta_{i1} - 2\angle \theta_i - \angle \theta_i = 180^\circ \\
 & \Rightarrow 3\angle \theta_{i1} - 3\angle \theta_i + \angle \theta_{rp1} = 180^\circ \\
 & \Rightarrow \angle \theta_{rp1} = 180^\circ - 3\angle \theta_{i1} + 3\angle \theta_i
 \end{aligned} \tag{2}$$

Figure 3(b) depicts the formation of the secondary reflected angle(θ_{rp2}) at the nanopillar interface after the primary reflected ray from the planar surface hits the proposed nanopillar interface. The value of this reflected angle could be formulated as:

$$\begin{aligned}
\theta_{r1} &= 90^\circ - (\theta_i + \theta_{rp2}) \\
\Rightarrow \theta_i + \theta_{rp2} &= 90^\circ - \theta_{r1} \\
\Rightarrow \theta_{rp2} &= 90^\circ - \theta_{r1} - \theta_i \\
\Rightarrow \theta_{rp2} &= 90^\circ - (\theta_{r1} + \theta_i)
\end{aligned} \tag{3}$$

The reverting angle from the trapezoidal cut (θ_m) at the planar surface could be denoted as,

$$\begin{aligned}
&\text{In } \Delta PQR, \\
&\angle P + \angle Q + \angle R = 180^\circ \\
&\Rightarrow 2\angle \theta_{rp2} + 90^\circ + \angle \theta_i + 90 - \theta_m = 180^\circ \\
&\Rightarrow 2\angle \theta_{rp2} + \angle \theta_i + 90 - \angle \theta_m = 0 \\
&\Rightarrow \angle \theta_m = 2\angle \theta_{rp2} + \angle \theta_i + 90
\end{aligned} \tag{4}$$

The attainment of optimum light absorbance within the proposed nanostructure on a largely relies on the total number of nanopillars placement over the circular detector's surface. Moreover, the interpillar spacing value is another pivotal factor which contributes towards trapping maximum incoming photons and providing adequate space to undergo internal multiple reflection mechanism. Figure.4(a)-(d) demonstrates the comparison of the various interpillar spacing in order to attain the maximum light absorption. Five incoming photons at 40° incident are considered to be trapped within the proposed array for the analysis.

(a)

(b)

(c)

(d)

Fig.4. Schematic comparison of various interpillar spacing(s) required for attaining maximum light absorbance at fixed nanopillar height (h): (a) ' $s < h$ ' (b) ' $h = s$ ' (c) ' $s > h$ ' (d) optimum spacing

Figure 4(a) provides the cross sectional view of the proposed nanopillar structure with interpillar spacing ' $s < h$ ' where, ' h ' represents the nanopillar height. As could be verified from the figure, two out of five incoming photons are trapped within the proposed nanopillar array. Although the trapped incoming photons undergo a large number of internal reflections for enhanced light absorption rate however an adequate amount of photons couldn't be trapped inside. This will increase the requirement of additional placement of the nanopillars increasing the device manufacturing cost.

Figure 4(b) provides the cross sectional schematic of the proposed nanopillar structure depicting the interpillar spacing ' $h = s$ '. As could be depicted from the figure, with this interpillar spacing three out of five incoming photons could be trapped within the array but they undergo only a few internal reflections. Due to this the trapped photons couldn't aid much towards enhanced light absorbance.

Figure 4(c) provides the cross sectional view of the nanostructure with interpillar spacing ' $s > h$ '. As the figure shows with this interpillar spacing although

a maximum number of incoming photons could be trapped inside the structure however, the last incoming photons hitting the planar detector's surface directly gets lost to air without facing any further internal reflection. Also, the incident photons striking the nanopillar interface couldn't get enough of the internal reflections for obtaining optimum absorbance as the distance to the adjacent nanopillar increases.

Figure 4(d) provides the interpillar spacing value where the last trapped incoming photon could hit the $(n_t-1)^{th}$ trapezoidal cut where, n_t represents a pair of the trapezoidal cut. With this internal spacing the trapped photons could get maximum of internal reflections inside the nanopillar array enhancing the light reabsorption probability to maximal level.

The value of this optimum interpillar spacing could be deduced as:

$$\begin{aligned}
 s &= s' + s'' \\
 \Rightarrow s &= \frac{(n_t - 1)(b_1 + b_2) + \frac{1}{2}b_1}{\tan(90^\circ - \theta_m)} + \frac{b_1 + b_2}{2 \tan(90^\circ - \theta_m)} \\
 \Rightarrow s &= \frac{2(n_t - 1)(b_1 + b_2) + b_1}{2 \tan(90^\circ - \theta_m)} + \frac{b_1 + b_2}{2 \tan(90^\circ - \theta_m)} \\
 \Rightarrow s &= \frac{2n_t(b_1 + b_2) - b_2}{2 \tan(90^\circ - \theta_m)} \quad (5)
 \end{aligned}$$

Here, ' b_1 ' and ' b_2 ' represent the upper and lower base length of the trapezoidal nanotextured cut

The most significant factor responsible towards achieving enhanced light absorbance is the deployment of the adequate number of total number of proposed nanopillars (N_p) over the circular detector's surface area with radius ' R '. Figure.5 depicts the pattern followed by the deployed nanopillars over the circular surface.

Fig.5 Layout representing total number of proposed nanopillar deployment over a circular detector's surface area of radius ' R '

The value of this nanopillar placement could be deduced as follows:

$$\text{Total area of the circular detector's planar surface} = \Pi R^2$$

$$\Rightarrow \Pi \left[\frac{N_p}{2}(d+s) + r \right]^2 = \Pi R^2$$

$$\Rightarrow \Pi \left[\frac{N_p^2}{4}(d+s)^2 + 2\frac{N_p}{2}(d+s)r + r^2 \right] = \Pi R^2$$

$$\Rightarrow \frac{N_p^2}{4}(d^2 + 2ds + s^2) + N_p(d+s)r + r^2 = R^2$$

$$\Rightarrow N_p^2(d^2 + 2ds + s^2) + 4N_p(d+s)r + 4r^2 = 4R^2$$

$$\begin{aligned}
N_p &= \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \\
\Rightarrow N_p &= \frac{-4r(d+s) + \sqrt{[4r(d+s)]^2 - 4[4r(d+s)]^2 16(r^2 - R^2)}}{2(d+s)^2} \\
\Rightarrow N_p &= \frac{-4r(d+s) + \sqrt{4r^2(d+s)^2 - 4(d+s)^2 16(r^2 - R^2)}}{2(d+s)^2} \\
\Rightarrow N_p &= \frac{-4r(d+s) + \sqrt{4(d+s)^2 [r^2 - 16(r^2 - R^2)]}}{2(d+s)^2} \\
\Rightarrow N_p &= \frac{-4r(d+s) + 2(d+s)\sqrt{-15r^2 + R^2}}{2(d+s)^2} \\
\Rightarrow N_p &= \frac{\sqrt{R^2 - 15r^2} - 2r}{(d+s)} \tag{6}
\end{aligned}$$

$$\text{Here, } d = \sqrt{4r^2 - a^2}$$

Where, ‘r’ is the radius of the octagonal faced nanopillar and ‘a’ denotes the side length of the octagonal shape.

We have,

$$s = \frac{2n_t(b_1 + b_2) - b_2}{2 \tan(90^\circ - \theta_m)}$$

Putting value of ‘s’ and ‘d’ in eqn. (6), we get,

$$N_p = \frac{[2 \tan(90^\circ - \theta_m)] [\sqrt{R^2 - 15r^2} - 2r]}{[2 \tan(90^\circ - \theta_m)] (\sqrt{4r^2 - a^2}) + 2n_t(b_1 + b_2) - b_2} \tag{7}$$

The nanopillar filling ratio (f) is the important parameter in determining the optimum number of nanopillars required for mitigating the light reflectance. This nanopillar filling ratio could be formulated as follows:

$$f = \frac{d}{p}$$

Where, ‘d’ is the diameter of the octagonal pillar cross section depicted in Fig. 5 and ‘p’ is the pitch length denoted by $p = d + s$.

Therefore, $f = \frac{d}{d+s}$ (8)

From eqn.(6),

$$N_p = \frac{\sqrt{R^2 - 15r^2} - 2r}{(d+s)}$$

$$\Rightarrow N_p = \frac{\sqrt{R^2 - 15r^2} - 2r}{(d+s)}$$

$$\Rightarrow N_p (d+s) = \sqrt{R^2 - 15r^2} - 2r$$

$$\Rightarrow N_p d + N_p s = \sqrt{R^2 - 15r^2} - 2r$$

$$\Rightarrow N_p d = \sqrt{R^2 - 15r^2} - 2r - N_p s$$

$$\Rightarrow d = \frac{\sqrt{R^2 - 15r^2} - 2r - N_p s}{N_p}$$

Putting this value in eqn.(8) we get,

$$f = \frac{\left[\sqrt{R^2 - 15r^2} - (2r + N_p s) \right] N_p}{N_p \left[\sqrt{R^2 - 15r^2} - (2r + N_p s) + s N_p \right]}$$

$$\Rightarrow f = \frac{\sqrt{R^2 - 15r^2} - (2r + N_p s)}{\sqrt{R^2 - 15r^2} - (2r + N_p s) + s N_p} \quad (9)$$

Putting the value of 's' in eqn. (8) we get,

$$f = \frac{\sqrt{R^2 - 15r^2} - (2r + N_p) \left[\frac{2n_t(b_1 + b_2) - b_2}{2 \tan(90^\circ - \theta_m)} \right]}{\left\{ \sqrt{R^2 - 15r^2} - (2r + N_p) \left[\frac{2n_t(b_1 + b_2) - b_2}{2 \tan(90^\circ - \theta_m)} \right] + \left[\frac{2n_t(b_1 + b_2) - b_2}{2 \tan(90^\circ - \theta_m)} \right] \right\}}$$

$$f = \frac{2 \tan(90^\circ - \theta_m) \sqrt{R^2 - 15r^2} - (2r + N_p) [2n_t(b_1 + b_2) - b_2]}{(\sqrt{R^2 - 15r^2} - 2r) + (N_p + 1) [2n_t(b_1 + b_2) - b_2]}$$

Now, the effective refractive index (n_{eff}) of a nanopillar structure is given as [15]:

$$\begin{aligned}
 n_{eff} &= n_{air}(1-f) + n_{GaSb}f \\
 \Rightarrow n_{eff} &= n_{air} - f(n_{air} + n_{GaSb}) \\
 \Rightarrow n_{eff} &= n_{air} - (n_{air} + n_{GaSb}) \left\{ \frac{2 \tan(90^\circ - \theta_m) \sqrt{R^2 - 15r^2} - (2r + N_p)[2n_t(b_1 + b_2) - b_2]}{(\sqrt{R^2 - 15r^2} - 2r) + (N_p + 1)[2n_t(b_1 + b_2) - b_2]} \right\} \quad (10)
 \end{aligned}$$

Considering zero transmission loss the Fresnel reflectance could simply be deduced as:

$$\text{Total light absorption} + \text{Total reflectance} = 1$$

With the proposed core-shell based octagonal faced nanopillar array the total obtained reduced reflectance for the ' N_{ph} ' number of trapped incoming photons out of which ' m ' incoming photons gets directly incident on the nanopillar interface while the remaining photons hits the nanopillar interface after striking the planar detector's surface could be calculated as:

$$\begin{aligned}
R &= m \left\{ r_{p1} - \left[r_{p1} A_{p2} + r_{p1} r_{p2} A_{p1} + r_{p1} r_{p2} r_{p1} A_{p2} \right] \right. \\
&\quad \left. + (N_{ph} - m) \left\{ r_s - \left[r_s A_{p1} + r_s r_{p1} A_{p2} + r_s r_{p1} r_{p2} A_{p1} \right] \right\} \right. \\
&\quad \left. \left\{ r_{p1} - \left[r_{p1} A_{p2} + r_{p1}^{(n-n_{x-1})} r_{p2}^{(n-n_{x-1})} A_{p1} \right. \right. \right. \\
&\quad \left. \left. + r_{p1}^{(n-n_{x-2})} r_{p2}^{(n-n_{x-1})} A_{p2} + r_{p1}^{(n-n_{x-2})} r_{p2}^{(n-n_{x-2})} A_{p1} \right. \right. \\
&\quad \left. \left. + r_{p1}^{(n-n_{x-3})} r_{p2}^{(n-n_{x-2})} A_{p2} + r_{p1}^{(n-n_{x-3})} r_{p2}^{(n-n_{x-3})} A_{p1} \right. \right. \\
&\quad \left. \left. + r_{p1}^{(n-n_{x-4})} r_{p2}^{(n-n_{x-3})} A_{p2} + \dots + r_{p1}^n r_{p2}^n A_s \right] \right\} \\
&\quad \left. + (N_{ph} - m) \left\{ r_s - \left[r_s A_{p1} + r_s r_{p1}^{(n-n_{x-1})} A_{p2} \right. \right. \right. \\
&\quad \left. \left. + r_s r_{p1}^{(n-n_{x-1})} r_{p2}^{(n-n_{x-1})} A_{p1} \right. \right. \\
&\quad \left. \left. + r_s r_{p1}^{(n-n_{x-2})} r_{p2}^{(n-n_{x-1})} A_{p2} \right. \right. \\
&\quad \left. \left. + r_s r_{p1}^{(n-n_{x-2})} r_{p2}^{(n-n_{x-2})} A_{p1} \dots \right] \right\} \\
&\Rightarrow R = m \left\{ r_{p1} - A_{p1} \left[r_{p1}^{(n-n_{x-1})} r_{p2}^{(n-n_{x-1})} \right. \right. \\
&\quad \left. \left. + r_{p1}^{(n-n_{x-2})} r_{p2}^{(n-n_{x-2})} \right. \right. \\
&\quad \left. \left. + r_{p1}^{(n-n_{x-3})} r_{p2}^{(n-n_{x-3})} \right] \right. \\
&\quad \left. + A_{p2} \left[r_{p1} + r_{p1}^{(n-n_{x-2})} r_{p2}^{(n-n_{x-1})} \right. \right. \\
&\quad \left. \left. + r_{p1}^{(n-n_{x-3})} r_{p2}^{(n-n_{x-2})} \right. \right. \\
&\quad \left. \left. + r_{p1}^{(n-n_{x-4})} r_{p2}^{(n-n_{x-3})} \right] + \dots + r_{p1}^n r_{p2}^n A_s \right\} \\
&\quad \left. + (N_{ph} - m) \left\{ r_s - A_{p1} r_s \left[1 + r_{p1}^{(n-n_{x-1})} r_{p2}^{(n-n_{x-1})} \right. \right. \right. \\
&\quad \left. \left. + r_{p1}^{(n-n_{x-2})} r_{p2}^{(n-n_{x-2})} \right] \right. \\
&\quad \left. + A_{p2} r_s \left[r_{p1}^{(n-n_{x-1})} \right. \right. \\
&\quad \left. \left. + r_{p1}^{(n-n_{x-2})} r_{p2}^{(n-n_{x-1})} \right] \dots \right\} \quad (11)
\end{aligned}$$

Here,

r_{p1} = Reflectance obtained from first nanopillar interface
 r_{p2} = Reflectance obtained from second nanopillar interface
 r_{ps} = Reflectance obtained from planar detector's surface.

The terms ' r_{p1} ' and ' r_{p2} ' includes reflectance from the four sides of the trapezoidal cut such as:

$$\begin{aligned}
 r_{p1}(\theta_{p1}) &= \frac{n_{air} \cos \theta_{p1} - n_{GaSb} \cos \theta_{tp1}}{n_{air} \cos \theta_{p1} + n_{GaSb} \cos \theta_{tp1}}, \\
 r_{p1}(\theta_{rp1}) &= \frac{n_{air} \cos \theta_{rp1} - n_{GaSb} \cos \theta_{trp1}}{n_{air} \cos \theta_{rp1} + n_{GaSb} \cos \theta_{trp1}}, \\
 r_{p1}(\theta_{rp2}) &= \frac{n_{air} \cos \theta_{rp2} - n_{GaSb} \cos \theta_{trp2}}{n_{air} \cos \theta_{rp2} + n_{GaSb} \cos \theta_{trp2}}, \\
 r_s &= \frac{n_{air} \cos \theta_i - n_{GaSb} \cos \theta_t}{n_{air} \cos \theta_i + n_{GaSb} \cos \theta_t}
 \end{aligned}$$

III. Results and Discussion

This section presents the simulative results of the effect of the proposed p-n radial homojunction based core-shell GaAs/GaSb cone topped octagonal faced nanopillar array structure over the photodetector performance metrics through Mie scattering formalism. The GaSb passivation layer act as the protective layer minimizing the surface defects present on the surface of the nanopillar structure. This defects free surface would prohibit surface recombination of the photogenerated exciton pairs. The structural parameters of the proposed model have been varied in order to verify its behaviour with changing light incident angle and various operating wavelengths. For the convenient simulative representation, a bunch of ten incoming photon rays at 30° angular incident to be emitted from a 3mm diameter GaAs source are considered to get trapped within the nanopillar array mounted over detector's circular front surface area of radius(R) 50um. The trapezoidal base lengths in our analysis has been mostly considered to be of 0.1um and 0.2um respectively. The main concept behind the reflectance mitigation with the proposed nanostructure model is enhancing the optical path length which would enhance their reabsorption probability

inside the device. This multiple reflection mechanism could boost up the reabsorption probability of the otherwise unabsorbed amount of light to a significant level.

Figure 6 illustrates the light absorption efficiency obtained with varying GaAs based core thickness as well as GaSb based shell thickness. As could be observed from the figure, with bare GaAs based 30nm core thickness without GaSb passivating layer a low 0.8 au absorption efficiency has been obtained. This is owing to the presence of surface defects. However, with the application of GaSb based passivating layer there is a suppression to the negative impact of surface defects. This could reduce the surface reflectance and produced exciton pairs doesn't get engulfed in the surface defects. Thus, with increasing the shell thickness there is a great enhancement in the overall light absorption efficiency. A maximum of 1.561 au at 20nm GaSb shell thickness has been attained at 500nm operating wavelength.

Fig.6. Variation of light absorption efficiency obtained at different core and shell thickness from 0nm to 30nm operating wavelength range of 0.5 μm to 1 μm

The variation of scattering efficiency obtained with non passivated GaAs based core as well as with GaSb passivating layers with varying thickness has been provided in Fig.7. As could be well evaluated from the figure that with increasing GaSb shell thickness there is huge suppression of the surface defects which would ultimately decrease the amount of incoming light scattering enhancing the absorption efficiency. A 25nm thick GaSb passivating layer over the 30nm thick core layer would the surface scattering efficiency to a value of 2.04 au at 500 nm.

Fig.7. Variation of scattering efficiency obtained with varying shell thickness from 10nm to 25nm at fixed core shell thickness of 30nm.

Apart from the core-shell based configuration the proposed nanopillar structure the adoption of the trapezoidal cut based nanotexture over the nanopillar surface could further increase the absorption efficiency of the incoming photons to a significant level. The adoption of appropriate cutting angles (θ_{t1} and θ_{t2}) plays a significant role in enhancing the photoresponsivity of the device. Depending on the cutting angles of the trapezoidal textured cut there could be a large increment in the internal multiple reflections of the incoming photons. This multiple reflection phenomenon could increase the optical path length to a greater extend which could boost the reabsorption probability. As could be illustrated from the Figure 8, with increasing

upper tilted angle of the trapezoidal cut, there is a gradual enhancement of the absorption efficiency due to the increased probability of the incoming photon to revert back to get reabsorbed at the nanopillar interface after striking the upper trapezoidal cut. A maximum 0.999 absorbance has been obtained with 50° trapezoidal tilted angle. However, increasing the tilted cut beyond 50° will decrease the overall absorption efficiency. This is due to the small reverting angle formed by the higher tilted trapezoidal cut. This small reverting angle will make the incoming photons to get directly lost to air after undergoing only certain amount of internal reflections.

Fig.8. Light absorption efficiency obtained with varying nanopillar textured cutting angle at operating wavelength of 0.5um to 1um.

Figure.6.9 demonstrates the variation of optimum interpillar spacing required for different angular light incidence at fixed trapezoidal cut pairs. As could be observed from the figure, with increasing angle of incidence, a smaller interpillar gap would produce enough light absorbance efficiency. This is because large angle of light incidence could revert back the incoming photon towards the planar detector's

surface after getting reflected from the interface of the upper trapezoidal cut . For smaller interpillar gap the secondary reflected ray again from this point would be get lost to air without interacting with the adjacent nanopillar. Similarly, for smaller incident angle, the reverted angle is large therefore, instead of striking back at the detector's surface it would hit the adjacent interpillar interface if the interpillar gap is not that large enough. From Figure.4(d) it was evaluated that for obtaining maximum number of internal reflections within the interpillar gap the reverting reflected ray should strike the detector's planar surface before hitting the adjacent nanopillar interface. Therefore, a larger interpillar spacing is required for smaller light incident angle for mitigating the light reflectance losses a significant level. Also for a longer proposed nanopillar structure or in other words for a larger number of trapezoidal cut pairs there will be a large interpillar spacing required for trapping the maximum number of incoming photons without requiring large number of deployed nanopillars.

Fig.9. Optimum interpillar spacing required at various photon incident angle for fixed pairs of trapezoidal cuts over a nanopillar.

The variation of total number of required nanopillars that could be deployed over a fixed circular detector's surface area depending on the light incident angles at fixed

pairs of trapezoidal is depicted for attaining maximum light absorbance is depicted in Figure.10.As could be well evaluated from the figure, at large incident angles a reduced interpillar gap is required to obtain maximal absorbance.This is because the incoming photons who gets trapped inside the array with large angular incidence requires the adjacent nanopillar to be placed nearer so as to obtain multiple internal reflections.Thus,there is a greater requirement of the total number of nanopillars that have to be deployed over the circular detector's surface for attaining maximum light absorbance.With increased number of trapezoidal cuts there is a lower requirement of nanopillars deployment as number of trapped incoming photons within the interpillar spacing for longer nanopillars is higher.A maximum of 3000 nanopillars are required to be deployed over a circular detector's surface with an interpillar spacing of 0.43 um for light angular incidence of 80^0 .

Fig.10. Total number of nanopillars deployment over a circular detector's surface of radius 'R' with fixed pairs of nanopillar trapezoidal cuts.

Figure 11 illustrates the variation of the filling ratio (f) obtained with increasing light incident angle for fixed nanopillar diameter. As illustrated with increased angle of incidence there is a reduction in the interpillar spacing required for mitigating light reflectance losses as illustrated. Due to this reduced interpillar spacing more number of proposed nanopillars could be deployed over the fixed 50um radius of circular

detector's surface. This automatically increases the filling ratio of the photodetector. With increased nanopillar diameter the area covered by a single proposed nanopillar is larger. This increases the coverage of the nanopillars over the detector's surface.

Fig.11. Variation of nanopillar filling ratio(f) with photon incident angle at fixed nanopillar diameter (d)

Figure 12 compares the total light absorbance attained with the proposed textured GaAs/GaSb material based trapezoidal cut based core shell nanopillar structure with planar faced core shell octagonal nanopillar structure and a flat GaAs based photodetector's surface. As illustrated the trapezoidal texturization based core-shell nanopillar array produces an enhanced absorbance of 0.999 at 40° light incident angle as compared to 0.745 and 0.27 absorbance with planar faced core shell octagonal nanopillar array and a flat detector's surface. With a radial GaAs based homo junction along with the GaSb passivated layer there is an overall reduction in the surface defects which minimizes the trapping of the photogenerated pairs and thus, enhancing the carrier collection efficiencies. With the addition of trapezoidal cut over the core shell based nanopillar structure there is a further significant increment attained in the overall light absorbance due to the increased multiple internal reflection phenomenon which enhances the optical path length of the incoming photon.

Fig.12.Total light absorbance comparison of the proposed textured core-shell nanopillar array,planar core-shell nanopillar array and without nanopillar deployment over the detector's surface w.r.t incoming light angle.

Figure13,14,15 provides the photoresponsive curves of the proposed GaAs/GaSb core shell octagonal faced trapezoidal textured cut based nanopillar array to that of planar faced octagonal core shell nanopillar array and flat detector's detector's surface in terms of responsivity, EQE and Detectivity. Enhanced carrier absorption attained with the proposed nanopillar array structure exhibits higher electron-hole pair generation leading towards attainment of 0.999 A/W responsivity at 1 mW input optical in comparison to the 0.75A/W and 0.5A/W with the planar faced core shell nanopillar array and flat detector's surface respectively at 1 μ m operating wavelength. The external quantum efficiency (EQE) performance of 89% also has a boost of approx 10% in comparison to that of 78% EQE obtained with the planar faced core shell nanopillar array and only 40% EQE with flat detector's surface at a narrow 0.5 μ m depletion width. For a bandwidth of 20GHz with 0.3nA darkcurrent and 1K load resistance at 300K temperature a maximum detectivity of 42.5x10³ $\sqrt{\text{Hz/W}}$ has been obtained at 1 μ m operating wavelength.

Fig.13. Photoresponse characteristic comparison of the device with proposed core-shell based trapezoidal textured based nanopillar array surface, planar core shell nanopillar array and flat detector's surface without nanopillar deployment for various wavelength range with parameters: $h=0.8\mu\text{m}$, $f=0.3$ and depletion width (w_d)= $0.6\mu\text{m}$

Fig.14.EQE(η) of the photodetector obtained with proposed textured core shell nanopillar array based surface($h=0.6\mu m, f=0.3\mu m, d=0.2\mu m$), planar core shell nanopillar array and flat surface($w_s=0.5\mu m$) for a wavelength range of $0.5\mu m$ to $1.1\mu m$ with a $0.6\mu m$ depletion width

Fig.15. Detectivity comparison of the proposed with proposed textured core shell nanopillar array based surface ($h=0.6\mu m, f=0.3\mu m, d=0.2\mu m$), planar core shell nanopillar array and flat surface($w_s=0.5\mu m$) for a wavelength range of $0.5\mu m$ to $1.1\mu m$ for 20GHz bandwidth and 0.3nA dark current.

IV. Conclusion

A periodically arranged GaAs/GaSb core-shell octagonal faced trapezoidal nanotextured based nanopillar array model has been proposed to be inlayed over a circular planar photodetector's front detector's surface made up of GaAs material of radius 'R' in order to mitigate the Fresnel light reflectance losses which has been arised due to the air-semiconductor refractive mismatch. Thekey phenomenon that contributes towards the attainment of the overall light reflectance mitigation is the multiple internal reflections mechanism that took place within the interpillar gap of the two adjacent nanopillar of the proposed nanopillar array structure.This multiple reflection phenomenon could enhance the optical path length of the incoming photon by enhancing their reabsorption probability which boost up the total light absorbance significantly.The whole mechanism is directly impacted by GaSb passivation over the GaAs p-n radial homojunction that could reduce the surface defects reducing the scattering of the incoming photons as well as the structural parameters in terms of the

tilted angle of the proposed trapezoidal cuts, nanopillar interpillar spacing and the pairs of trapezoidal cuts. The proposed nanopillar array structure exhibits 87% EQE with a photoresponsivity of 0.995 A/W at 1 μ m operating wavelength.

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