Optical modelling of a GaAs/GaSb core–shell cone-topped octagonal-faced nanopillar array with periodic trapezoidal textured cut for high photon trapping efficiency

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Received: 4 February 2022 / Accepted: 26 April 2022 / Published online: 11 June 2022 © The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

Abstract
Light reflectance mitigation is the most crucial factor for achieving optimal photodetector performance. In this respect, light-trapping mechanisms based on nanostructures or microstructures such as nanopillars, nanocones and nanopyramids have emerged as the most promising candidate for reducing overall light reflectance. This is because of their large effective irradiation area, multiple scattering of incident light and increased path length of incident rays in these nanostructures. This paper proposes an optical model of a GaAs/GaSb material-based vertically oriented core–shell cone-topped octagonal nanopillar structure with periodical trapezoidal nanotexturization over it to be deployed on a circular planar detector surface with a radius of 50 μm. The geometric analytical investigation of the proposed model reveals 0.999 overall absorbance, 0.995A/W photoresponsivity, and 87% EQE at 1 μm operating wavelength.

Keywords External quantum efficiency · Nanopillar · Photoresponsivity · Reflectance · trapezoidal textured cut

1 Introduction
Photodetector performance efficiency greatly depends upon the ability to achieve optimal photon absorption and efficient carrier collection [1, 2]. Vertical nanopillars have emerged as the most promising candidate for attaining high light absorbance efficiency. This can be attributed to their unique light-trapping mechanism through specular reflectance [3]. The proper tailoring of the nanopillar structural parameters such as diameter, length and pitch scale length can tremendously enhance the light absorption efficiency [4, 5]. In order to promote further enhancement of light absorbance efficiency, textured nanostructures exhibit extraordinary optical effects through the multiple light scattering phenomenon. For example, single-layer GaAs-based nanopyramids prepared through a combination of lithography, metal-enhanced chemical vapour deposition and gas-phase substrate removal provide remarkable absorption at a wider radiation spectrum and a broad incident angle range at large curvature bending [6]. A 2 μm-thick integrated-nanopillar-nanowell (i-NPW) array coated with a 40 nm silicon layer provides an integrated absorption of approximately 89% [7]. Surface texturing of silicon with oblique nanopillars reduces light reflection to less than 10% [8]. Besides attaining optimal light absorbance, light collection efficiency is another
significant factor influencing the efficiency of photodetector performance. To this end, thin films have previously been adopted to improve carrier collection efficiency [9]. However, film thickness was found to be a critical parameter. Exciton pairs which are generated more than one diffusion length from the p–n junction space region lead to diminishing carrier efficiency [10]. Also, they consist of high-density recombination sites [11]. This constraint is overcome by the core–shell nanopillar structure. The core–shell p–n junction embedded in the nanopillar structure allows the orthogonalization of the photon absorption and carrier collection direction [12, 13]. The minority carriers thus travel a shorter path length than the minority diffusion length. Moreover, the outer shell acts as a passivation layer for the inner core which can suppress the surface states [14]. Additionally, these shell layers consisting of high-bandgap material prevent carrier recombination at the surface [15].

In previous work, the authors have demonstrated the effect of nanotexturization on vertical nanopillar structures to mitigate the total light reflectance phenomenon, including GaAs-based nanotextured pyramidal-cut nanopillar array [16], InGaAs-based hexagonal nanopillar array [17], right triangular texturized GaAs-based square nanopillar deployed on the front photodetector surface [18] and half-octagonal cut-based hexagonal nanopillar array, on light reflectance minimization for high photodetector responsivity [19]. However, to boost the light absorbance to the next level and for maximum trapping of incoming photons, the nanopillar structure has been upgraded to octagonal-faced.

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

2 Optical modelling of the nanopillar array structure

The optical modelling of the internal light reflectance pattern in the proposed nanopillar array structure was done using geometric ray optics. The structural parameters, material filling ratio and performance parameters of the nanopillar array were analysed using numerical methodologies. The simulation of the device characterization was carried out using MATLAB software. Figure 1a depicts a schematic representation of the proposed GaAs/GaSb-based core–shell cone-topped octagonal-faced radial p–n homojunction vertical nanopillar array structure on which periodically patterned trapezoidal cut-based nanotexturization has been done. The core consists of two layers of p-GaAs and n-GaAs material of radius $r_1$ and $r_2$, respectively. The GaSb passivation layer consists of a layer thickness of $t \mu m$. The trapezoidal-based nanotextured base lengths are denoted by $b_1$ and $b_2$, with $s$ being the interpillar gap deployed on the front surface area of a circular detector with diameter $D$. To demonstrate the light reflectance pattern in the nanopillar array, geometric ray optics has been adopted. For the analytical investigation, a bunch of five photons operating at 900 μm wavelength is considered to be emitted from a 3 mm-diameter GaAs light-emitting diode (LED) source.

The benefit of the adopted trapezoidal-based nanotextured cut as compared with the previously adopted nano-textures [16, 18, 19] is illustrated in Fig. 2.

The analytical investigation of the light reflectance in the proposed cone-topped octagonal-faced nanopillar model with trapezoidal nanotextures over it was compared with the previously proposed right triangular nanotextures and pyramidal-cut textures on the octagonal-faced nanopillar structure. For the geometric ray analysis, two 30° incident incoming photons are considered to be trapped in the interpillar gap of the nanopillar array.

Figure 2a depicts the internal light reflectance pattern in the previously proposed periodically arranged pyramidal cut-based nanotexture adopted in the currently 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. The first incoming ray (Ph-1) strikes the detector’s front surface at an incident angle of 30°. After some amount of absorption takes place in 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 $\theta_2$. This photon, after undergoing only three internal reflections, is lost to air without contributing to enhanced light absorption.
The light reflectance pattern in the interpillar gap of the prior proposed right-angle texture-based octagonal-faced nanopillar array is depicted in Fig. 2b. As can be seen, this nanopillar structure provides a larger number of internal multiple reflections to the incoming photons as compared with the previous pyramidal model. The first incoming photon undergoes seven internal reflections, increasing the photon absorption path length. Similarly, the second incoming photon undergoes six internal reflections within the interpillar space, increasing the light absorption efficiency.

Figure 2c depicts the light reflectance in the proposed cone-topped GaAs/GaSb-based core–shell octagonal-faced nanopillar array structure with trapezoidal nanotexture on it. As is well illustrated in the figure, the first incoming photon undergoes a maximal number of nine internal reflections, while the second incoming photon undergoes a maximum of seven internal reflections in the structure before being lost to air. Thus, it can be easily seen that the proposed trapezoidal-based nanotexture provides the maximum number of internal reflections to the incoming light trapped in the nanopillar array. This phenomenon of internal reflections increases the photon absorption path length to a maximal level, thus reducing the incoming signal loss to the minimum level.

The enhancement of the optical absorption path length is completely dependent on the total internal reflections faced by the incoming photons in the proposed nanopillar structure. These internal reflections are completely reliant on the striking angles of the incoming photons at the nanopillar interfaces as well as their reflection angles over the detector’s planar surface. Figure 3a, b depicts these angular parameters of the incident photon on the proposed nanopillar structure. The formation of the incident angle ($\theta_{p1}$) on the trapezoidal textured interface of the nanopillar array structure is illustrated in Fig. 3a. The trapezoidal textured structural parameters include lower cutting angles
(θ_{t1} and θ_{t2}) of 50° each, while the upper cutting angles (θ_{u1} and θ_{u2}) are both 40°. The upper and lower base lengths of the trapezoid are termed 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 can be deduced as follows:

\[ \text{In } \triangle BCM, \]
\[ \angle B + \angle BCD + \angle M = 180^\circ \]
\[ \Rightarrow \angle B_{t2} + 90^\circ - \angle 1 + 90^\circ - \angle \theta_{i} = 180^\circ \]
\[ \Rightarrow \angle \theta_{t2} + 90^\circ - \angle \theta_{p1} + 90^\circ - \angle \theta_{i} = 180^\circ \]
\[ \Rightarrow \angle \theta_{p1} = \angle \theta_{t2} - \angle \theta_{i} \]

(1)

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

\[ \text{In quadrilateral ABCD,} \]
\[ \angle A + \angle B + \angle C + \angle D = 360^\circ \]
\[ \Rightarrow \angle \theta_{u1} + \angle 3 + \angle 4 + \angle 1 + \angle 2 + 180^\circ - \angle \theta_{p} = 360^\circ \]
\[ \Rightarrow \angle \theta_{u1} + \angle \theta_{p1} + \angle \theta_{rp1} + \angle x + \angle \theta_{p1} + 180^\circ - (90 - \angle \theta_i) = 360^\circ \]
\[ \Rightarrow \angle \theta_{u1} + 2\angle \theta_{p1} + 2\angle \theta_{rp1} + 90^\circ - \angle \theta_{p1} + 90^\circ - \angle \theta_{i} = 360^\circ \]
\[ \Rightarrow \angle \theta_{u1} + \angle \theta_{p1} + 2(\angle \theta_{t2} - \angle \theta_{i}) + 90^\circ + 90^\circ - \angle \theta_{i} = 360^\circ \]
\[ \Rightarrow \angle \theta_{u1} + \angle \theta_{p1} + 2\angle \theta_{t2} - 2\angle \theta_{i} + 180^\circ - \angle \theta_{i} = 360^\circ \]
\[ \Rightarrow \angle \theta_{u1} + \angle \theta_{p1} + 2\angle \theta_{t2} - 2\angle \theta_{i} = 180^\circ \]
\[ \Rightarrow 3\angle \theta_{u1} - 3\angle \theta_{i} + \angle \theta_{p1} = 180^\circ \]
\[ \Rightarrow \angle \theta_{p1} = 180^\circ - 3\angle \theta_{u1} + 3\angle \theta_{i} \]

(2)

Figure 3b 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 can be formulated as

\[ \theta_{t1} = 90^\circ - (\theta_{i} + \theta_{rp2}) \]
\[ \Rightarrow \theta_{i} + \theta_{rp2} = 90^\circ - \theta_{t1} \]
\[ \Rightarrow \theta_{rp2} = 90^\circ - \theta_{t1} - \theta_{i} \]
\[ \Rightarrow \theta_{rp2} = 90^\circ - (\theta_{t1} + \theta_{i}) \]

(3)

The reflection angle from the trapezoidal cut (θ_{m}) at the planar surface can be denoted as
The attainment of optimal light absorbance in the proposed nanostructure largely relies on the total number of nanopillars placed on the circular detector surface. Moreover, the interpillar spacing value is another pivotal factor contributing to maximum trapping of incoming photons and providing adequate space to undergo the internal multiple reflection mechanism. Figure 4a–d demonstrates a comparison of the various interpillar spacing values in order to attain the maximum light absorption. Five incoming photons at 40° incident angle are considered to be trapped within the proposed array for the analysis.

Figure 4a provides a cross-sectional view of the proposed nanopillar structure with interpillar spacing \( s < h \), where \( h \) represents the nanopillar height. As can be seen, 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, an adequate number of photons cannot be trapped inside. This will increase the need for additional placement of nanopillars, increasing the device manufacturing cost.

Figure 4b provides a cross-sectional schematic of the proposed nanopillar structure depicting the interpillar spacing \( h = s \). As can be seen, with this interpillar spacing, three out of five incoming photons can be trapped within the array, but they undergo only a few internal reflections. For this reason, the trapped photons have little effect on enhancing the light absorbance.

Figure 4c provides a 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 can be trapped inside the structure, the last incoming photons hitting the planar detector surface are directly lost to air without undergoing any further internal reflection. Also, the incident photons striking the nanopillar interface cannot undergo enough internal reflections to obtain optimal absorbance as the distance to the adjacent nanopillar increases.

Figure 4d provides the interpillar spacing value where the last trapped incoming photon can hit the \((n-1)th\) trapezoidal cut, where \( n \) represents a pair of the trapezoidal cuts. With this internal spacing, the trapped photons can undergo the maximum internal reflections inside the nanopillar array, enhancing the light reabsorption probability to the maximal level.

\[
\begin{align*}
\text{In } \triangle PQR, \\
\angle P + \angle Q + \angle R &= 180^0 \\
\Rightarrow 2\angle \theta_{p2} + 90^0 + \angle \theta_i + 90 - \theta_m &= 180^0 \\
\Rightarrow 2\angle \theta_{p2} + \angle \theta_i + 90 - \theta_m &= 0 \\
\Rightarrow \angle \theta_m &= 2\angle \theta_{p2} + \angle \theta_i + 90 
\end{align*}
\]
The value of this optimal interpillar spacing can be deduced as follows:

\[
\begin{align*}
    s &= s' + s'' \\
    \Rightarrow s &= \left( n_i - 1 \right) \left( b_1 + b_2 \right) + \frac{1}{2} b_1 \left( 90^\circ - \theta_m \right) + \frac{b_1 + b_2}{2 \tan \left( 90^\circ - \theta_m \right)} \\
    \Rightarrow s &= \frac{2 \left( n_i - 1 \right) \left( b_1 + b_2 \right) + b_1 + b_2}{2 \tan \left( 90^\circ - \theta_m \right)} \\
    \Rightarrow s &= \frac{2n_i \left( b_1 + b_2 \right) - b_2}{2 \tan \left( 90^\circ - \theta_m \right)}
\end{align*}
\] (5)

Fig. 4 Schematic comparison of various interpillar spacing values required for attaining maximum light absorbance at fixed nanopillar height \( h \): a \( s < h \), b \( h = s \), c \( s > h \), and d optimal spacing

Fig. 5 Layout representing the total number of proposed nanopillar deployment on a circular detector surface area of radius \( R \)
Here, \( b_1 \) and \( b_2 \) represent the upper and lower base length of the trapezoidal nanotextured cut.

The most significant factor responsible for achieving enhanced light absorbance is the deployment of an adequate total number of proposed nanopillars (\( N_p \)) on the circular detector surface area with radius \( R \). Figure 5 depicts the pattern of the deployed nanopillars over the circular surface.

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

Total area of the circular detector’s planar surface = \( \pi R^2 \)

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

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

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

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

Putting the values of \( s \) and \( d \) in Eq. (6), we get

\[
N_p = \frac{2n_s (b_1 + b_2) - b_2}{2 \tan (90^0 - \theta_m)}
\]

Putting the values of \( s \) and \( d \) in Eq. (6), we get

\[
N_p = \frac{[2 \tan (90^0 - \theta_m)] \left[ \sqrt{R^2 - 15r^2} - 2r \right]}{[2 \tan (90^0 - \theta_m)] \left( \sqrt{4r^2 - a^2} + 2n_s (b_1 + b_2) - b_2 \right)}
\]

(7)

The nanopillar filling ratio (\( f \)) is an important parameter in determining the optimal number of nanopillars required for mitigating the light reflectance. This nanopillar filling ratio can 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 Eq. (6),

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

\[
\Rightarrow N_p = \sqrt{R^2 - 15r^2} - 2r
\]

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

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

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

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

Putting this value in Eq. (8), we get
The structure is given as [15]:

\[
\frac{\sqrt{R^2 - 15r^2} - (2r + N_p s)}{N_p \sqrt{R^2 - 15r^2} - (2r + N_p s) + sN_p}
\]

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

Putting the value of \( s \) in Eq. (8), we get

\[
f = \frac{\sqrt{R^2 - 15r^2} - (2r + N_p \frac{2n_i(b_1 + b_2)}{2 \tan(90^0 - \theta_m)}}
\]

\[
\Rightarrow f = \frac{2 \tan(90^0 - \theta_m) \sqrt{R^2 - 15r^2} - (2r + N_p) [2n_i(b_1 + b_2) - b_2]}{\sqrt{R^2 - 15r^2} - 2r} + (N_p + 1) [2n_i(b_1 + b_2) - b_2]
\]

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

\[
n_{eff} = n_{air}(1 - f) + n_{GaSb}f
\]

\[\Rightarrow n_{eff} = n_{air} - f (n_{air} + n_{GaSb})
\]

\[\Rightarrow n_{eff} = n_{air} - (n_{air} + n_{GaSb}) \frac{2 \tan(90^0 - \theta_m) \sqrt{R^2 - 15r^2} - (2r + N_p) [2n_i(b_1 + b_2) - b_2]}{\sqrt{R^2 - 15r^2} - 2r} + (N_p + 1) [2n_i(b_1 + b_2) - b_2]
\]

Considering zero transmission loss, the Fresnel reflectance can simply be deduced as follows:

Total light absorption + 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 are directly incident on the nanopillar interface, while the remaining photons hit the nanopillar interface after striking the planar detector surface, can be calculated as follows:

\[
R = m \left\{ r_{p_1} - \left[ r_{p_1}A_{p_2} + r_{p_1}r_{p_2}A_{p_1} + r_{p_1}r_{p_2}r_{p_3}A_{p_1} + \ldots \right] + \left[ r_{p_1}A_{p_2} + r_{p_1}r_{p_2}A_{p_1} + \ldots \right] \right\} + (N_{ph} - m) \left\{ r_{s} - \left[ r_{p_1}A_{s} + r_{p_1}r_{p_2}A_{p_1} + r_{p_1}r_{p_2}r_{p_3}A_{p_1} + \ldots \right] + r_{p_1}A_{s} + \ldots \right\}
\]

\[
\Rightarrow R = m \left\{ r_{p_1} - \left[ \frac{r_{p_1}A_{p_2} + r_{p_1}r_{p_2}A_{p_1} + r_{p_1}r_{p_2}r_{p_3}A_{p_1} + \ldots}{r_{p_1}A_{p_2} + r_{p_1}r_{p_2}r_{p_3}A_{p_1} + \ldots} \right] + \left[ r_{p_1}A_{p_2} + r_{p_1}r_{p_2}A_{p_1} + \ldots \right] \right\} + (N_{ph} - m) \left\{ r_{s} - \left[ \frac{r_{p_1}A_{s} + r_{p_1}r_{p_2}A_{p_1} + r_{p_1}r_{p_2}r_{p_3}A_{p_1} + \ldots}{r_{p_1}A_{s} + r_{p_1}r_{p_2}A_{p_1} + \ldots} \right] + r_{p_1}A_{s} + \ldots \right\}
\]

Here,

\[r_{p_1} = \text{Reflect} \tan \text{ce obtained from first nanopillar interface}\]

\[r_{p_2} = \text{Reflect} \tan \text{ce obtained from second nanopillar interface}\]

\[r_{p_3} = \text{Reflect} \tan \text{ce obtained from planar detector's surface}\]

The terms \( r_{p_1} \) and \( r_{p_2} \) include reflectance from the four sides of the trapezoidal cut:
3 Results and Discussion

This section presents the simulation results of the effect of the proposed p–n radial homojunction-based core–shell GaAs/GaSb cone-topped octagonal-faced nanopillar array structure on the photodetector performance metrics through Mie scattering formalism. The GaSb passivation layer acts as a protective layer minimizing the surface defects present on the surface of the nanopillar structure. This defect-free surface prevents surface recombination of the photogenerated exciton pairs. The structural parameters of the proposed model are varied in order to verify its behaviour with the change in light incident angle and various operating wavelengths. For convenient simulation, a bunch of ten incoming photon rays at 30° angular incident to be emitted from a 3 mm-diameter GaAs source are considered to become trapped within the nanopillar array mounted on the detector’s circular front surface area of radius \( R \) 50 μm. The trapezoidal base lengths in our analysis are mostly considered to be of 0.1 μm and 0.2 μm, respectively. The main concept behind the reflectance mitigation with the proposed nanostructure model is enhancing the optical path length, which would enhance the reabsorption probability inside the device. This multiple reflection mechanism can boost 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 and GaSb-based shell thickness at different thickness. As can be observed from the figure, with bare GaAs-based 30 nm core thickness without a GaSb passivation layer, a low 0.8 au absorption efficiency is obtained. This is owing to the presence of surface defects. However, with the application of the GaSb-based passivation layer, the negative impact of surface defects is suppressed. This reduces the surface reflectance, and the exciton pairs produced are not trapped in the surface defects. Thus, with increasing shell thickness, the overall light absorption efficiency is greatly enhanced. A maximum of 1.561 au at 20 nm GaSb shell thickness is attained at an operating wavelength of 500 nm.

The variation in scattering efficiency obtained with the non-passivated GaAs-based core and with GaSb passivation layers with varying thickness is provided in Fig. 7. As can be clearly seen, with increasing GaSb shell thickness, the surface defects are significantly suppressed, which ultimately decreases the amount of incoming light scattering, thus enhancing the absorption efficiency. A 25 nm-thick GaSb passivation layer over the 30 nm-thick core layer results in surface scattering efficiency of 2.04 au at 500 nm.

Apart from the core–shell-based configuration of the proposed nanopillar structure, the adoption of the trapezoidal cut-based nanostructure on the nanopillar surface significantly further increases the absorption efficiency of the incoming photons. The adoption of appropriate cutting...
angles ($\theta_{t1}$ and $\theta_{t2}$) plays a significant role in enhancing the photoresponsivity of the device. Depending on the cutting angles of the trapezoidal textured cut, a large increase in the internal multiple reflections of the incoming photons can be attained. This multiple reflection phenomenon increases the optical path length to a greater extent, which improves the reabsorption probability. As illustrated in Fig. 8, with an 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 be reflected back and be reabsorbed at the nanopillar interface after striking the upper trapezoidal cut. A maximum of 0.999 absorbance is obtained with a 50° trapezoidal tilted angle. However, increasing the tilted cut beyond 50° will decrease the overall absorption efficiency. This is due to the small reflection angle formed by the higher tilted trapezoidal cut. This small reflection angle will cause the incoming photons to be directly lost to air after undergoing only a certain number of internal reflections.

Figure 9 demonstrates the variation in optimal interpillar spacing required for different angular light incidence at fixed trapezoidal cut pairs. As can be observed from the figure, with an increasing angle of incidence, a smaller interpillar gap produces sufficient light absorbance efficiency. This is because a large angle of light incidence can reflect back the incoming photon towards the planar detector surface after being reflected from the interface of the upper trapezoidal cut. For a smaller interpillar gap, the secondary reflected ray again from this point would be lost to air without interacting with the adjacent nanopillar. Similarly, for a smaller incident angle, the reflection 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 large enough. From Fig. 4d it can be seen that to obtain a maximum number of internal reflections within the interpillar gap, the reflected ray should strike the detector’s planar surface before hitting the adjacent nanopillar interface. Therefore, larger interpillar spacing is required for smaller light incident angles to mitigate the light reflectance losses at a significant level. Also, for a longer proposed nanopillar structure, or in other words for a larger number of trapezoidal cut pairs, large interpillar spacing will be required for trapping the maximum number of incoming photons without requiring a large number of deployed nanopillars.

The variation in the total number of required nanopillars that can be deployed on a fixed circular detector surface area depending on the light incident angles at fixed trapezoidal pairs for attaining maximum light absorbance is depicted in Fig. 10. As can be easily seen, at large incident angles, a reduced interpillar gap is required to obtain maximal absorbance. This is because the incoming photons that are trapped inside the array with large angular incidence require the adjacent nanopillar to be placed nearer so as to obtain multiple internal reflections. Thus, a greater total number of nanopillars must be deployed on the circular detector surface to attain maximum light absorbance. With the increased number of trapezoidal cuts, fewer nanopillars need to be deployed as the number of incoming photons trapped in the interpillar space for longer nanopillars is higher. A maximum of 3000 nanopillars must to be deployed on a circular detector surface with an interpillar spacing of 0.43 μm for light angular incidence of 80°.

Figure 11 illustrates the variation in the filling ratio ($f$) obtained with increasing light incident angle for a fixed nanopillar diameter. As illustrated, with increased angle of incidence, there is a reduction in the interpillar spacing required to mitigate light reflectance losses. Due to this
reduced interpillar spacing, more proposed nanopillars can be deployed on the fixed 50 μm radius of the circular detector 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 on the detector’s surface.

Figure 12 compares the total light absorbance attained with the proposed textured GaAs/GaSb trapezoidal cut-based core–shell nanopillar structure with a planar-faced core–shell octagonal nanopillar array and without nanopillar deployment on the detector surface with respect to incoming light angle.

![Fig. 10 Total number of nanopillars deployed on a circular detector surface of radius \( R \) with fixed pairs of nanopillar trapezoidal cuts](image1)

![Fig. 11 Variation in nanopillar filling ratio \( f \) with photon incident angle at fixed nanopillar diameter \( d \)](image2)

![Fig. 12 Total light absorbance comparison of the proposed textured core–shell nanopillar array, planar core–shell nanopillar array and without nanopillar deployment on the detector surface with respect to incoming light angle](image3)

core–shell octagonal nanopillar array and flat detector surface. With a radial GaAs-based homojunction along with the GaSb passivated layer, an overall reduction in surface defects is achieved, which minimizes the trapping of the photogenerated pairs, thus enhancing the carrier collection efficiency. With the addition of a trapezoidal cut on the core–shell-based nanopillar structure, a further significant increase in the overall light absorbance is attained due to the increased multiple internal reflection phenomenon, which enhances the optical path length of the incoming photon.

Figures 13, 14 and 15 provide the photoresponsivity 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 surface in terms of responsivity, external quantum efficiency (EQE) and detectivity. Enhanced carrier absorption attained with the proposed nanopillar array structure exhibits higher electron–hole pair generation leading to the attainment of 0.999 A/W responsivity at 1 mW input optical as compared with the 0.75A/W and 0.5A/W with the planar-faced core–shell nanopillar array and flat detector surface, respectively, at 1μm operating wavelength. The EQE performance of 89% is also an increase of approximately 10% in comparison with that of 78% EQE obtained with the planar-faced core–shell nanopillar array and only 40% EQE with a flat detector surface at a narrow 0.5 μm depletion width. For a bandwidth of 20 GHz with 0.3 nA dark current and 1 K load resistance at temperature of 300 K, maximum detectivity of 42.5 × 10^3√Hz/W is obtained at 1 μm operating wavelength.
4 Conclusion

A periodically arranged GaAs/GaSb core–shell octagonal-faced trapezoidal nanotextured-based nanopillar array model has been proposed to be inlaid on the front surface of a circular planar photodetector composed of GaAs material of radius \( R \) in order to mitigate the Fresnel light reflectance losses which arise due to the air–semiconductor refractive mismatch. The key phenomenon contributing to the attainment of the overall light reflectance mitigation is the multiple internal reflection mechanism that occurs within the interpillar gap of the two adjacent nanopillars of the proposed nanopillar array structure. This multiple reflection phenomenon enhances the optical path length of the incoming photons by enhancing their reabsorption probability, which significantly increases the total light absorbance. The whole mechanism is directly impacted by GaSb passivation over the GaAs p–n radial homojunction that can 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 pairs of trapezoidal cuts. The proposed nanopillar array structure exhibits 87% EQE with photoresponsivity of 0.995 A/W at an operating wavelength of 1 \( \mu \)m.

**Funding** The authors have not disclosed any funding.

**Data Availability** Enquiries about data availability should be directed to the authors.

**Declarations**

**Conflict of interest** The authors have not disclosed any competing interests.
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