Introduction

Global energy demand will more than double (or more) by 2050, which is particularly worrisome if we do not efficiently use solar irradiance in the near future [1]. The average intensity of solar irradiance that is available on Earth in 1 hour is equal to $4.3 \times 10^{20} \text{ J}$ energy, which is equivalent to the energy we consume in 1 year [2], that is, 13 TW. According to Lewis [3], covering 0.16% of the planet with 10% efficient solar cells could provide 20 TW of power. This result indicates that we can produce more power than the annual global requirement by covering $<0.16\%$ of the Earth using more efficient low-cost solar cells with an efficiency of more than 25%. Light trapping or confinement in the 3–4 nm diameter structure is quite challenging and must consider different structures and textures [4]. We must increase the supply of Si materials and reduce the cost of photovoltaic device fabrication processes.

One improvement method is to use less Si and low-cost processing methods to create high-efficiency tandem solar cells using Si nanowire (NW) based heterojunction solar cells [4–6]. Another method is to choose cheap and simple growth processes to reduce the fabrication cost of photovoltaic devices. In principle, Si nanostructures can absorb light and directly generate electrons and holes, if they have the same wavelength as the size of the energy gap [5, 7]. There are several unique advantages of Si NWs, that is, the band gap in Si NWs can be transformed from an indirect into a direct-induced band gap via quantum size effects, high crystallinity, self-assembly, high surface-to-volume ratios, and slow electron–hole recombination as compared to the bulk or thin films [5, 6, 8–19]. Si NWs developed using the top-to-bottom approach were
explained by Li et al. [20], who showed that power conversion efficiency has made huge progress (to nearly 12%) in <10 years. Wallentin et al. fabricated an InP NW photovoltaic (PV) device, for which 13.8% conversion efficiency was achieved [21, 22]. Si NW-based solar cells are promising for facilitating carrier collection due to the nanostructure size of vertically aligned and ordered arrays of Si NWs. In this way, we can offer straight pathways for carrier collection to escape the device as quickly as possible before recombining in the Si NW-based photovoltaic device [23].

Among bottom-up Si NW growth methods, vapor liquid solid (VLS) mode-based Si NW growth is getting a great deal of attention because of its low-cost processing technique [24]. There have been many reports of bottom-up Si NW growth methods using various materials as a catalyst, such as Au, Al, Ga, In, Pb, Sn, and Zn, via VLS mechanisms [7, 9, 10, 25–33]. Au-catalyzed Si NWs grown using VLS might not be useful for solar cell applications because they create a deep acceptor level at 0.54 eV in the Si band gap, whereas the In catalyst creates a shallow acceptor level at 0.16 eV in the Si band gap and can suppress the degradation of minority carrier lifetime [32]. Recently, we successfully controlled the verticality of Si NWs with good crystalline quality. In-catalyzed based Si NWs grown using the VLS mode produced cone-shaped Si NWs because of catalyst trapping by the NWs [32, 33]. Ball et al. [34], investigated the optical characteristics of conical Si NWs and focused on the influence of the Sn catalyst thickness layer and NWs densities on the optical characteristics.

The cone-shaped (CS) pin-Si NW structure could provide a promising path toward cost-effective, Si-based nano-devices including tandem solar cells grown using the VLS growth mode because of the efficient absorption of photons [35–41]. There are several reports available on the optical modeling and simulation of different geometrical shapes, sizes, and materials. [42–51]. Few years ago, optical properties of c-Si nanohole array structures for solar photovoltaic applications were investigated [42] and it was found that the nanohole absorption is better than nanorod arrays for solar cells application. Foldyna et al. [43], found that when double-diameter nanowire arrays were used for solar cell, then $I_{sc}$ increased up to 10% using optical simulation model. Recently, shape-dependent power conversion efficiency (PCE) of Si NW, solar cells with polygonal cross-sectional shapes, including trigon, tetragon, hexagon, and circle, were investigated [44] based on the atomic-bond-relaxation (ABR) approach and detailed balance principle. In this investigation, one claim was made that the classical detailed balance principle can be extended to the nanometer scale through ABR consideration, which considers the effect originated from the end relaxation, including surface and edge parts of the NWs [44]. Moreover, five different shapes (cylindrical, truncated conical, convex conical, conical, and concave conical) of silicon NW arrays arranged in a square are studied [45], and, if the cross section of silicon NW is changed into a square, both light trapping and effective light absorption are enhanced, and the Eiffel Tower-shaped NW arrays have optimal effective light absorption [45]. Geng et al. [46], used FDTD simulation model, and found that the absorption efficiency of optimized random Si NW radial p-n junction array reaches 27.8% compared with a value of ordered Si NWs radial p-n junction array, which is 19.9%. The influence of assembly structure and monotonic grating structures on the optical absorption were also investigated here [47]. And it was found that the assembly structure yields a higher spectral absorptance and conversion efficiency of solar cells as compared to the monotonic grating and nanorod structures because of the combined effects of nanorod and grating components [47]. One interesting research problem about tuning the UV emission of the ZnO–ZnS core–shell nanorod arrays by changing the index of the substrate were investigated [48], and it was concluded that the introduction of active host medium is responsible for the optical absorption, which was greater than the expected Lambert–Beer law [48]. Michallon et al. [49], rigorously investigated the optical behavior of extremely thin absorber solar cells based on ZnO/CdTe core–shell nanowire (NW) arrays with square, hexagonal, or triangular arrangements, using three-dimensional rigorous coupled wave analysis (RCWA). It was concluded that the light absorption is more efficient in the NW square arrangement than in the hexagonal and triangular arrangements [49]. The same author undertook the comparative studies of optical properties of Si and ZnO/CdTe core/shell nanowire arrays and it was revealed that core–shell nanowire arrays made of ZnO/CdTe can more efficiently absorb light than that of the Si [50]. Li et al., found that the silicon nanocube (SiNC) base diameter should be equal to the array periodicity for efficient solar energy harvesting, and the optimized light absorption could be realized when the SiNC height reaches ~400 nm [51].

Theoretically speaking, the optical properties of silicon can be strongly affected by injection of charge carriers ($\Delta N$) into an undoped sample. However, there is no experimental report in the Si literature on spectral changes via free carrier injection/depletion. On the other hand, there are few references that show the effects of impurity doping on the optical properties of bulk silicon (Si) film [52, 53]. The influence of density $N_i$ of impurity atoms on the variation of absorption spectrum, in the bulk crystal is experimentally known [52]. There are no reports on the optical simulation model of CS-pin-Si NW that
consider the influence of refractive indices on the absorption due to the charge carrier injection into the pin region of cone-shaped NWs. Therefore, in this research article, the influence of top diameter and periods (in the context of charge carrier injection into the doped region of CS-pin-Si NW solar cells) on the optical absorption were investigated using the FDTD modeling method. The reason why we choose FDTD will be explained in the next section.

Methods

The simulation model should be as realistic as possible, so that it can be correlated with the experimental application of the desired photovoltaic device structure, including CS-pin-Si NWs solar applications. For reliable modeling, it is essential to obtain the electromagnetic field with high accuracy such that near-field effects, which have a strong influence on the final value of light absorption in the NWs, can be evaluated. In line with this point of view, some approximations such as coupled-mode theory do not give us more reliable and accurate information about absorption in NW-based top cells for tandem structure applications because coupled mode theory does not take into account the contribution of the near-field effects [40, 41].

Using numerical methods, we can solve Maxwell’s equations in the time-domain (such as using FDTD) or in the frequency domain [such as using the finite element method (FEM), RCWA, the FDFD method, or the multiple multipole method (MMP)]. FEM and FDTD methods have been extensively used in the literature to model the optical characterization of photovoltaic device structures including Si NWs Solar cells [46, 47]. However, the FDTD method is vulnerable to numerical errors such as numerical dispersion, and special care is needed during the implementation of the scheme.

In the FDTD method, the grid size might restrict the time-step duration; therefore, a finer mesh indicates a slower simulation. This disadvantage is even more pronounced when dispersive materials are used. If special care is taken, then the usefulness of using the FDTD method is that one can simulate a wide range of wavelengths in one run, which is a great advantage over other available numerical schemes. FDTD can also take into account the near-field effect.

Therefore, we choose an FDTD numerical method and used a fine mesh of roughly 2 nm to simulate the three-dimensional (3D) CS-pin-Si NW, as shown in Figure 1. In the remainder of the article, we will refer to the CS-pin-Si NW simply as NW.

The absorption that may occur for photon energies smaller than the bandgap is mainly due to the free carrier absorption and it is known fact that the free carrier absorption coefficient is proportional to the local carrier concentration [52]. And therefore the degree of optical confinement might be having strong influence on the spectral absorption factor for photons with an energy smaller than the bandgap, that is, for the case of long wavelength solar irradiance.

The cone-shaped axial NWs for PV cell can be represented by a multilayer structure (pin), each layer being characterized by a complex refractive index,

\[ N = n - ik \] (1)

where both the real refractive index \( n \) and the extinction coefficient \( k \), which are the functions of \( \lambda \), can be found in the literature [54, 55]. Note that the absorption coefficient \( \alpha \) and the extinction coefficient \( k \) are related as:

\[ \alpha = \frac{4\pi k}{\lambda}. \] (2)

It is obvious from equation (2) that \( \alpha \) decreases strongly with increasing wavelength [52]. Short wavelength photons (\( \lambda < 1000 \text{ nm} \)) have an energy larger than the bandgap, and therefore are able to create electron–hole pairs and can readily be absorbed by the crystalline silicon (c-Si). However, long wavelength photons (\( \lambda > 1200 \text{ nm} \)) cannot generate electron–hole pairs and are hardly absorbed by c-Si. Photons in the transition region (1000 nm < \( \lambda \) < 1200 nm) are weakly absorbed, that is, are only absorbed after having traveled some distance in the c-Si material.

Therefore, n- or p-type doping in to a semiconductor means that “free” electrons or holes are introduced. These free charge carriers can also absorb photons (but electron–hole pairs are not generated). Hence, the absorption
coefficient of silicon depends on n- and p-type doping concentration \( c_n \) and \( c_p \) [52, 53].

Soref and Bennett have experimentally found that the optical properties of Si can strongly be affected by the injection of charge carriers (\( \Delta N \)) into the undoped sample or by the removal of free carriers (\( -\Delta N \)) from a doped sample [52]. And it was assumed that the free carrier concentration (FCI) is equal to the dopant concentration. The influence of the refractive index change (\( \Delta n \)) of crystalline Si (c-Si) produced by an applied electric field (\( E \)) or by a change in the concentration of charge carriers (\( \Delta N \)) has been determined. The influence of a density \( N \) of impurity atoms on the variation of absorption spectrum in the bulk crystal has already been experimentally found. Changes in the optical absorption coefficient of the material (\( \Delta \alpha \)) at the wavelength of interest were observed and low-loss propagation were reported [52]. The refractive index change \( \Delta n \) calculated from the spectrum is assumed to be the value of \( \Delta n \) that arises from \( \Delta N \). The following well-known formulas for refraction and absorption due to free electrons and free holes, respectively, were used to calculate the refractive index (\( n \)), the extinction coefficient (\( k \)) values for the p-type c-Si, i-type c-Si, and n-type c-Si layers of the pin structure of the NW as shown in Figure 1:

\[
\Delta n = -e^2 \lambda^2 / 8\pi^2 c^2 \varepsilon_s \left( \frac{\Delta N_n}{m^*_e} + \frac{\Delta N_i}{m^*_i} \right)
\]

\[
\Delta \alpha = e^2 \lambda^2 / 4\pi^2 c^2 \varepsilon_s \left( \frac{\Delta N_n}{m^*_e \mu_e} + \frac{\Delta N_i}{m^*_i \mu_h} \right)
\]

where \( e \) is the electronic charge, \( \varepsilon_s \) is the permittivity of free space, \( n \) is the refractive index of unperturbed c-Si, \( m^*_e \) is the conductivity effective mass of electrons, \( m^*_i \) is the conductivity effective mass of holes, \( \mu_e \) is the electron mobility, and \( \mu_h \) is the hole mobility. The impurity of electron density, \( \Delta N_n = 10^{19} \text{ cm}^{-3} \), and hole density, \( \Delta N_i = 10^{19} \text{ cm}^{-3} \), were used in equations (3) and (4), respectively.

Then, the \( n \) and \( k \) values of the i-type c-Si, n-type c-Si, and p-type c-Si layer were calculated, which are shown in Figure 2(A and B). These \( n \) and \( k \) values were used in this model to investigate the influence of injected charge in the pin junction of the NWs. The detailed structure of the simulated NW-based top cell is shown in Figure 1, where the height of the NW was chosen to be 5 \( \mu \text{m} \), and the bottom diameter \( D_b = 150 \text{ nm} \) was kept fixed, with two different periods, that is, \( P_1 = D_b = 150 \text{ nm} \) and \( P_2 = 2D_b = 300 \text{ nm} \). In this model, the top diameter \( D_t \) of the NWs was varied from 70 nm to 110 nm and a periodic boundary condition was set along the \( x \) direction and the perfectly matched layer (PML) boundary condition was set along the \( z \) direction.

The AM 1.5 condition was used to calculate the short circuit current density (\( J_{sc} \)) in this model. It is well-known that sunlight is composed of both transverse electric (TE) and transverse magnetic (TM) modes, where TE is equivalent to TM because of the structural symmetry in NW. Therefore, we choose only the TE mode to investigate optical confinement in the NW. Air was taken as a background material for the NW, where the TE mode polarizes the incoming light such that the electric field is in the \( x \) direction, \( E_x \), and the magnetic field is in the \( y \) direction, \( H_y \). The wires have the same width and period in the \( x \) and \( y \) directions. The periodic boundary condition is also set in the \( y \) direction. The simulated region of Si NWs is represented by a cone-shaped frame in which
PMI boundary conditions and the source were assigned to the top and bottom, respectively. The reflectance and transmission sensor were placed at the top and bottom, respectively, of the NWs, as shown in Figure 1.

The optical generation rates and ultimate photocurrents were also calculated by using equation (5) after plugging the value of EQE (external quantum efficiency) and solar spectral irradiance. It is well-known that the photocurrent is an accumulative sum of the electron–hole pairs (EHPs) generated by the incident photons at different wavelengths of the solar spectrum. When the photons are absorbed in the active layer of the NWs, then they can completely contribute to the photocurrent, that is, if all of them generate EHPs and all of these EHPs are collected (assuming that the absorption in the other layers of the solar cell do not contribute to the photocurrent and under the perfect carrier extraction condition), then the short circuit current density of the solar cell can be written as:

$$J_{sc} = q ∫ \frac{λ}{hc} \Phi(λ)⋅EQE(λ) dλ$$  \hspace{1cm} (5)

where $λ$ is the wavelength of the incident photon, $h$ is Planck’s constant, $c$ is the speed of light in air, $q$ is the electron charge, $Φ$ is solar spectral irradiance, and EQE is the external quantum efficiency of the solar cell. In simpler terms, EQE indicates how much of the energy of the incident light is converted into electrical energy at each wavelength.

In this article, the influence of top diameter variation of the NWs and the period variation of the NWs regarding optical absorption in the NW top cell were investigated in the wavelength range between 300 and 1000 nm. The influence of the refractive index $n$ (wavelength variation was between 600 and 1000 nm for $p$-type $c$-Si, $i$-Si, and $n$-type $c$-Si, of axial pin structure NWs) on the light absorption was evaluated.

Results and Discussion

Absorption, reflection, and transmission were theoretically investigated for periods $P1$ and $P2$ for the wavelength range from 300 to 1000 nm as a function of $D_t$ of the NWs. The absorption was normalized by the entire incident light that irradiated both the NWs and air as a medium. When we used the absorption in the range of wavelengths shorter than 400 nm, we encountered large calculation errors in FDTD, and therefore, we used “absorption = 1 – reflectance ($R$) – transmittance ($T$)” data for absorption in the range of wavelengths shorter than 400 nm.

Figure 3(A–C) gives the simulated optical properties of the NW-based solar cells. In the shorter wavelength region (<600 nm), the absorption is independent of period but strongly depends on the top diameter of the NWs, as shown in Figure 3(A). On the other hand, in the long wavelength region (>600 nm), the absorption increases with the increase of top diameter $D_t = 110$ nm for period $P1$, which can be attributed to both the relatively small diameter and the periods for successive internal reflection. The highest absorption shoulder trend toward long wavelength was found at $D_t = 110$ nm, as shown in Figure 3(A). This trend of absorption is attributed to the reflectance behavior shown in Figure 3(B) in the same wavelength region. Furthermore, on the basis of our result, we realized that the exposed area of the NWs and the angle of incident light depend on the top diameter of the NWs, which might be responsible for causing enhancement of absorption value for $D_t = 110$ nm for period $P1$. We found that the absorption for period $P1$ and period $P2$ with $D_t = 30$ nm is almost the same as that in the low wavelength region (<600 nm), as shown in Figure 3(A); the same phenomenon is seen in the reflectance behavior, as shown in Figure 3(B). Note that the period, or optimization of the period, could cause enhanced absorption and suppressed reflection because of successive internal reflection from the neighboring NWs during efficient absorption. The reflectance of NWs with $D_t = 30$ nm for period $P1$ gives a reasonable value of <3% in the wavelength range between 300 and 600 nm; one abrupt peak was observed near 790 nm, as shown in Figure 3(B), which might be caused by the interference of light waves. Figure 3(C) gives the transmission behavior of NWs; relatively high transmission behavior was found in NWs with $D_t = 30$ nm for period $P2 = 300$ nm, than the NW with $D_t = 110$ nm and period $P1 = 150$ nm, in the high wavelength region (>500 nm). Furthermore, at wavelengths longer than 650 nm, the $n$ and $k$ values of $n$-type $c$-Si and $p$-type $c$-Si layers of $Si$ NWs are relatively large and interference effects can be reduced because of the oscillation of reflectance and transmittance.

The mapping in Figure 4 shows the distribution of the normalized electric field $E_x$ and $E_y$, and the normalized magnetic field, $H_y$, of the TE mode at irradiated light wavelengths of 500 nm and 700 nm for the period $P1 = 150$ nm with a top diameter $D_t = 30$ nm. Figure 4(A–C) shows the results with period $P1 = 150$ nm at a wavelength of 500 nm. Figure 4(D–F) shows the results with same period $P1$ at a wavelength of 700 nm. The cone shapes in the center of Figure 4(A–F) represent the pin structure of crystalline silicon solar cells. $E_x$ is concentrated in a very small area of the NWs, but occupies a large area of the air as a background, as shown in Figure 4(A). $E_z$ is confirmed to be at the edge of the NWs, as shown in Figure 4(C), which means that the incoming light is refracted toward the high refractive index ($n$) material,
that is, doped Si or undoped Si. On the other hand, as shown in Figure 4(B), the magnetic field is distributed uniformly near the top of the NWs both in air and in the NWs for the case of period P1, at 500 nm in wavelength. These behaviors of the electromagnetic field might be due to the boundary condition between the two different media and the top diameter in the context of the $n$ value of the n-type c-Si layer. The influence of refractive index variation on n-type c-Si layers at 500 nm caused by free carrier injection is negligible, as shown in Figure 2(A). The parallel magnetic field and vertical electric flux density of the material interface are continuous until the n-type c-Si layer is reached. Thus, when the diameter is smaller than the wavelength of the irradiated light, then the $H_y$ density distribution was found to be concentrated in the area near the NW and probably gives rise to the enhanced absorption at the wavelength of 500 nm.

For the NW arrangement with period P1 where the irradiated light has a wavelength of 700 nm was used, weak $E_x$ is concentrated in the p-layer of the NWs (bottom side of the NWs), and most of $E_z$ was concentrated in the air region, as shown in Figure 4(D). Some contribution of $E_z$ is confirmed at the edge of the NWs, as shown in Figure 4(F). The influence of refractive index variation on the p-type c-Si layer at 700 nm caused by free carrier injection is important, as shown in Figure 2(A), which shows a higher refractive index value at 700 nm as compared to both the i-Si layer and the p-type c-Si layer. Therefore, we speculate that a small contribution of absorption may be caused by the high refractive index values of the p-type c-Si layer of the pin structure of NWs in the wavelength range of roughly 700 nm. On the other hand, $H_y$ is concentrated uniformly over the entire area of NWs and in the region of air, for the case of period P1 at 700 nm in wavelength, as shown in Figure 4(E). This result further shows that $H_y$ is distributed over a large area at 700 nm in wavelength and confirms higher transmission and low absorption. If we compare this result with the case in Figure 4(B), $H_y$ is concentrated in the area near the NWs for the case of period P1 and a wavelength of 500 nm, which is probably caused by the parallel magnetic field density. The light at 500 nm in wavelength would not likely reach the flat space between each NW, as shown in Figure 4(A–F); therefore, the light shows high absorption (nearly 100% absorption) in this case.

The mapping in Figure 5 shows the distribution of the normalized electric field $E_{x}$, $E_{z}$, and the normalized magnetic field, $H_y$, of the TE mode at a wavelength of 500 nm and 700 nm, respectively, for a period P2 of 300 nm and

Figure 3. Optical characterization of the CS-pin-Si NW top cell with varying top diameters $D_t$ in the range of 30–70 nm, and with periods P1 and P2, for (A) absorption, (B) reflection, and (C) transmission.
Figure 4. Electric and magnetic fields of the electromagnetic waves in each direction of CS-pin-Si NW for the case of period P1, with top diameter $D_t = 30$ nm (A) $E_x$ at a wavelength of 500 nm, (B) $H_y$ at a wavelength of 500 nm, and (C) $E_z$ of Si NW at a wavelength of 500 nm, (D) $E_x$ of Si NW at a wavelength of 700 nm, (E) $H_y$ of Si NW at a wavelength of 700 nm, and (F) $E_z$ of Si NW at a wavelength of 700 nm. [Colour figure can be viewed at wileyonlinelibrary.com].

Figure 5. Electric and magnetic fields of the electromagnetic waves in each direction of CS-pin-Si NWs for the case of period P2, with $D_t = 30$ nm (A) $E_x$, (B) $H_y$, and (C) $E_z$ of Si NW at a wavelength 500 nm. (D) $E_x$, (E) $H_y$, and (F) $E_z$ of Si NW at a wavelength 700 nm. [Colour figure can be viewed at wileyonlinelibrary.com].
a $D_t$ value of 30 nm. Figure 5(A–C) show the results at a wavelength of 500 nm. Figure 5(D–F) show the results at a wavelength of 700 nm. $E_x$ is concentrated only in a very small area of the i-Si layer; however, highly concentrated distributions were found in the air region, as shown in Figure 5(A) and weak $E_z$ was confirmed at the edge of the NWs, as shown in Figure 5(C). On the other hand, as shown in Figure 5(B), $H_y$ is distributed uniformly, around the top of the n-type c-Si NWs both in air and in the NWs, at 500 nm in wavelength. A significant concentration of $H_z$ was observed throughout the NW layer, which, in this case, was without transmission.

For the case of light with a wavelength of 700 nm, with P2 relatively high, $E_x$ is concentrated in the p-layer of the NWs (bottom side of the NWs), and most of $E_x$ was concentrated in the air region, as shown in Figure 5(D), and a small contribution of $E_z$ was confirmed at the edge of the p-type c-Si NWs, as shown in Figure 5(F). On the other hand, as shown in Figure 5(E), $H_y$ is uniformly distributed over the entire area of the NWs and the air region at 700 nm in wavelength. This figure further shows that $H_y$ is distributed over a large area at 700 nm in wavelength and confirms a higher transmission and low absorption as compared to the case in Figure 5(B), where $H_y$ is concentrated in the nearby region in the NW, for the case of period P2 at 500 nm in wavelength.

The light absorption at specific wavelengths of interest, such as 500 nm and 700 nm, were also investigated for the case of periods P1 and P2, respectively. In the case of a wavelength of 500 nm, the absorption significantly increased and was found to be independent of the period (P1 or P2), as shown in Figure 6(A); however, the absorption increased slightly when we decreased the period from 300 to 150 nm at a wavelength of 700 nm. The same behavior was confirmed in the mapping of $E_x$, $E_z$, and $H_y$, as shown in Figure 4.

Perfect carrier extraction was assumed, and therefore, the EQE was assumed to be equal to the absorption. EQE for periods P1 and P2 for $D_t = 30$ nm were calculated; almost 100% values were observed below 550 nm in wavelength, as shown in Figure 6(B). Good light scattering was observed in the NW arrangement with period P1, as compared to P2 or bulk Si, because of the high value of successive internal reflections from the neighboring NWs. Additionally, a significant change of absorption between the short wavelength side and the long wavelength side were found for a top diameter $D_t$ of 70 nm, with period P1 = 150 nm for the NWs. The highest values of EQE were observed for period P1 with $D_t = 30$ nm in the wavelength region of <550 nm, as shown in Figure 6(B). Relatively high EQE values were observed in the wavelength

![Figure 6](image-url)
region of >600 nm for the $D_t = 110$ nm for period P1 in the NWs, which can be attributed to both the large value of the top diameter, and the high refractive index values in the p-type c-Si layer of the NWs. In practical applications, we must consider the influence of the interface condition and the good quality of the pin structure growth of NWs on EQE enhancement.

Short circuit current density for period P1 and P2 were calculated as a function of $D_t$ using equation (5). The $J_{sc}$ values were enhanced to as high as 19.2 mA/cm$^2$ when we reduce the period from 300 to 150 nm and increase $D_t$ up to 110 nm, as shown in Figure 6(C). However, $J_{sc}$ values of roughly 18.4 mA/cm$^2$ were achieved in the case of $D_t = 70$ nm with period P1 for a single NW. Note that the presence of cone-shaped NWs improves the photocurrent $J_{sc}$ in TE, which is observed when only one wire is present per period because of the difference of the effect of the NWs on $J_{sc}$ in the TE polarizations, and also because sunlight is not naturally polarized. One possible concern regarding the NWs is that they may interfere with carrier collection. This phenomenon can occur in different scenarios. First, the formation of voids/defects around the particle and poor material quality at the particle interface may create a high interface defect state density, thus causing problems for carrier collection. Second, voids or defects can reduce the influence of the internal electric field on the generated carriers and deviated carrier transform inside the NW solar cell. In the near future, these issues will be addressed in the context of CS-Si NW top cells for tandem solar cell applications.

In this part, the influence of the free carrier injection (FCI) on the absorption in CS-pin-SiNW for case with $D_t = 30$ nm and P1, were discussed as shown in Figure 7(A and B), where the free carrier concentration (FCI) is equal to dopant concentration. The Figure 7(A) gives the absorption for both the cases (with FCI and without FCI) for the wavelength range (600 < $\lambda$ < 900 nm). In this case, we found that the absorption was enhanced slightly for the case of without FCI than the case with FCI in p-type and n-type region of NW, respectively. Similarly, we also focused on the absorption for both the cases (with FCI and without FCI) for the wavelength range (300 < $\lambda$ < 600 nm), where the absorption was found to be independent of doping. However, small influence of free carrier absorption, on the absorption factor were realized in the 600 nm < $\lambda$ < 900 nm. And we also realize that it can be unexpectedly large in the long wavelength side due to the higher k-values as a function of n-type impurity doping in NWs as depicted from Figure 2(B). We need to investigate in detail the influence of doping on the absorption beyond the wavelength 1200 nm in the near future for the small band gap materials like Si$_{0.80}$Ge$_{0.20}$ NWs (band gap=1.0-0.98 eV) to exploit the solar irradiance on the long wavelength side.

### Conclusion

In this article, the influence of free carrier injection into the doped region of CS-pin Si NWs for solar cell applications (as a function of top diameter and periods) on the optical absorption was successfully evaluated. However, the small influence of free carrier absorption, on the absorption factor were realized in the 600 nm < $\lambda$ < 900 nm, but we realize that it can be unexpectedly large in the long wavelength side due to the higher k-values as a function of impurity doping in NWs. We found that light scattering caused by the cone-shaped Si NW structure with a period of 150 nm and a top diameter of 70 nm improves the optical confinement for solar cells applications grown using the VLS mode.
The absorption increased when we decreased the period from 300 to 150 nm for a wavelength of 700 nm. In the case of a wavelength of 500 nm, the absorption significantly increased by up to 100% and was found to be independent of the period. EQE for a period of 150 nm and top diameter of 30 nm reached almost 100% of the value at 550 nm in wavelength. The calculated $I_{sc}$ values were found to be as high as 19.2 mA/cm$^2$ in the case of a top diameter of 110 nm at a period of 150 nm. A reasonable $I_{sc}$ value of roughly 18.4 mA/cm$^2$ in the case of a top diameter of 70 nm with a period of 150 nm. These findings can play a significant role in realizing practical applications of CS-pin junction Si NW-based solar cells grown using the VLS mode for tandem solar cell applications.

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**Conflict of Interest**

None declared.

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