Enhanced photon absorption of single nanowire α-Si solar cells modulated by silver core

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Abstract: Single nanowire solar cells are a promising candidate as nanoelectronic power sources. Metallic cores were integrated in single nanowire solar cells, and the influence of the silver core on the absorption efficiency and the short circuit current was studied in this work. A Full-wave Vectorial Finite Element Method approach was used to rigorously solve Maxwell’s equations in two dimensions. The photon absorption in solar cells was modulated delicately to achieve higher absorption efficiencies and short circuit currents, by tuning the core size and radius of nanowire solar cells. The light trapping stemmed mainly from the localized surface plasmons and also from Mie scattering and leaky mode resonances. The results showed that an enhancement of 16.6% in the photocurrent could be achieved by α-Si nanowire solar cells with the proper core size and filling-ratio compared to that without silver core.

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References and links
1. Introduction

Single nanowire solar cells (SNSCs) represent a promising class of photovoltaic devices due to several outstanding performance features, including a direct path for charge transport [1], a reduced size for nano-integrated circuit [2], and a superior ability for light trapping [3,4]. Because of the excellent performance of single nanowire, their applications have extended into many nano-devices, such as tunnel diodes [5], transistors [6], thermoelectric devices [7,8], and lithium batteries [9]. In 2007, a photovoltaic device utilizing a single silicon nanowire has been fabricated, and its output power can reach up to 200 picowatts, which is robust to drive nanoelectronic sensors and logic gates [2]. Recently, SNSCs with various active layers are investigated either experimentally or theoretically [10–14].

Photon management in single nanowires provides a new approach to the high conversion efficiency in the SNSCs. It has been found that, by tuning the size of single nanowires, the leaky mode resonances (LMRs) in the nanowires can be optimized for photovoltaic cells [15,16]. To further enhance the absorption of sunlight, metallic nanostructures are conceived to be combined into solar cells, due to their unparalleled ability to concentrate light into sub-wavelength volumes [17]. Recently, a silver particle is utilized to improve the photocurrent in the SNSCs and the photocurrent increases at some wavelengths [18]. However, similar work directed to single nanowires is just the beginning. Assuming a metallic core is embedded into a single nanowire, then how the core structure would affect on light absorption in the single nanowire for photovoltaic application? Discussion on such a problem has never been reported yet; in fact, the metal core embedded in inorganic single nanowire [19] besides organic one [20] is already available using current nanotechnology.

In this work, we propose and demonstrate numerically the possibility of metallic-cores that enable strong optical absorption in single nanowire solar cells. Using full-wave finite element method, we have investigated how the metallic core can be exploited to modulate the absorption profile in the α-Si nanowire solar cells. The contribution of localized surface plasmons (LSPs), LMRs, and Mie scattering to light trapping are investigated by tuning the geometric profiles of core radius and nanowire radius. Finally, to maximize the benefit of the silver core, the structural optimization for SNSCs is carried out.

2. Optical model and numerical method

The simulation model is shown in Fig. 1. The single nanowire is treated as an infinitely long cylinder and characterized by the radius $R$. The silver core with radius $r$ is embedded into the
center of the single $\alpha$-Si nanowire. The normal incidence is along the $y$-axis as shown in Fig. 1. The computational domain considered is terminated by perfectly matching layers (PML). The gray and blue arrows in the non-PML region represent incident and scattered light respectively. In the simulation, electromagnetic (EM) field is assumed to be time harmonic and the resulting steady-state distribution is solved using scattered-field formulation. With the scattered-field formulation the incident plane wave is specified as a background field for all non-PML regions, so it is not at all affected by the PML design. It is worth noting that, with a total-field formulation, the plane wave excitation is difficult to set up in this model. The scattered field ($E_{\text{scat}}$) describes the difference between the background ($E_b$) and measurable total field ($E_{\text{tot}}$) caused by the presence of the scatter, that is, $E_{\text{scat}} = E_{\text{tot}} - E_b$ [21]. Then the governing equation is as following,

$$\nabla \times (\mu_r \nabla \times E_{\text{scat}}) - (\varepsilon_r - j \frac{\sigma}{\omega \varepsilon_0}) k_0^2 E_{\text{scat}} = 0. \tag{1}$$

where $\varepsilon_0$ is the vacuum permittivity, $\mu_0$ is the vacuum permeability, $k_0$ is the vacuum wave vector, $\omega$ is the angular frequency, $\varepsilon_r$ is the relative permittivity, $\mu_r$ is the relative permeability, and $\sigma$ is the electrical conductivity of the material.

The absorption profile in $\alpha$-Si absorber is calculated by $\frac{21}{2} \int \omega \varepsilon' (\omega) |\mathcal{E}\rangle^2 dv$, where $v$ is volume of silicon absorber layer, $|\mathcal{E}|^2$ is normalized light intensity at near field (incident plus scattered), $\varepsilon'$ is the imaginary part of dielectric function of amorphous silicon. Dispersive dielectric functions of $\alpha$-Si and Ag come from the experimental data of Paik [22]. The absorption efficiency is calculated by $Q_{\text{abs}} = C_{\text{abs}} / C_{\text{geom}}$ [23], where $C_{\text{abs}}$ is the absorption cross section, and $C_{\text{geom}}$ is the geometrical cross-section. The absorption cross section is equal to the difference between extinction and scattering, i.e., $C_{\text{abs}} = C_{\text{ext}} - C_{\text{scat}}$. For non-polarized sunlight, the absorption efficiency is obtained by averaging the values of both s-polarized and p-polarized light, i.e., $Q_{\text{abs}} = \frac{Q_{\text{abs}}^s + Q_{\text{abs}}^p}{2}$. Here, $Q_{\text{abs}}^s$ and $Q_{\text{abs}}^p$ are the absorption efficiencies for s-polarized (E-field vector points out of the x-y plane, along the z-axis) and p-polarized (E-field parallels to the x-y plane, along x-axis) illuminations respectively.

To investigate the potential benefit of the metallic-core for solar cells, the ultimate photocurrent density or short-circuit current density, $J_{sc}$, is calculated according to the following equation:

$$J_{sc} = \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} \frac{\varepsilon' \lambda}{hc} Q_{\text{abs}} (\lambda) \Phi_{\text{AM1.5}} (\lambda) d\lambda. \tag{2}$$
where $Q_{abs}$ is the absorption efficiency, $e/hc$ is the charge constant, $\Phi_{AM1.5}$ is the reference solar spectral irradiance (ASTM G-173) [24]. To match the solar spectrum to $\alpha$-Si absorption, a wavelength range from 400 to 800 nm is considered.

3. Results and discussion

3.1 Influence of the core on photon absorption for SNSCs with radius of 150 nm

Firstly, photon absorption in the SNSCs with silver core is compared with that without silver core to explore the mechanism of light absorption. Then, the effect of core radius on light trapping in the SNSCs is discussed. It is worth noting that, in this subsection, 150 nm is chosen as the radius of SNSCs. The reason is that there is no LMRs existed in SNSCs with such a size, which is discussed in the following subsection. In such a case, all the influence on absorption is ascribed to the silver core, and then the interaction of silver core with LMRs need not to be considered in this system, which facilitates greatly the investigation on the mechanism of light trapping.

Figure 2(a) shows the representative spectra of $Q_{abs}$ in the SNSCs with and without silver core. The radius of SNSCs and the core are chosen as 150 nm and 50 nm respectively. As shown in Fig. 2(a), the $Q_{abs}$ spectra can be divided into three regions labeled I, II, and III, for both s-polarized and p-polarized illumination. In Region I, between 400 and 480 nm, the $Q_{abs}$ spectra for the two structures are almost overlapping together. In Region II, from 480 to 620 nm, the $Q_{abs}$ spectra of the SNSCs with silver core are a little lower than that without silver core. In Region III, where the wavelengths are greater than 620 nm, the $Q_{abs}$ spectra of the SNSCs with silver core increase greatly than that without silver core. The absorption efficiency being greater than unity for p-polarized illumination, as shown in Fig. 2(a), is ascribed to internal photocurrent gain [25].

To investigate the mechanism of light absorption, the normalized absorption profiles in SNSCs with and without silver core are plotted in Fig. 2(b). The absorption profiles in Region I, II and III are given by exemplifying the profiles at the wavelength of 450 nm, 550 nm, and 668 nm, respectively. As shown in Fig. 2(b), the upper (1-6) and lower groups (7-12) of profiles are corresponding to the wavelength of 450 nm, 550 nm, and 668 nm respectively.

![Fig. 2. (a) Comparison of absorption efficiency, $Q_{abs}$, between the SNSCs with (w) and without (w/o) silver core. The radius of SNSCs, $R$, is 150 nm and the inner core, $r$, is 50 nm. (b) Normalized absorption profiles in the SNSCs with and without silver core for s-polarized (upper) and p-polarized (lower) illumination. The profiles in column I, II and III are corresponding to the wavelength of 450 nm, 550 nm, and 668 nm respectively.](image)
nm, the incoming photon energy is fully absorbed at the surface before reaching the center position. Therefore, the silver core can take little effect on the absorption behavior, which is the reason why the $Q_{abs}$ curves are almost overlapped together. In Region II, e.g., 550 nm, the light penetrates deeper and converges near the center place in the $\alpha$-Si nanowire. In such a case, if the central part of $\alpha$-Si nanowires is replaced by the silver core, the effective volume of the absorber will reduce greatly (more than 11%, for the silver core with radius of 50 nm). Consequently, the corresponding $Q_{abs}$ decrease a little for both s- and p-polarized illumination. With increasing the wavelength of incident light, the influence of volumetric reduction is won over by the integrated effect of Mie scattering and localized surface plasmons (LSPs), resulting in a substantial improvement of $Q_{abs}$ in Region III. The Mie scattering is characterized by the “8”-like scattering pattern, where the forward and backward scattering, with respect to the incident direction of light, have greater intensity than that of the other directions. The role of Mie scattering is determined by the characteristic absorption profile of SNSCs, as shown in profile 6 in Fig. 2(b), where the forward and backward “hot spots” can be observed clearly. The “hot spots” represent the absorption magnitude, and they are proportional to the scattering pattern. Meanwhile, as shown in Fig. 2(a), the absorption peak at about 668 nm for s-polarized light, corresponding to the profile 6, is also ascribed to Mie scattering. As shown in Fig. 2(a), there is also a distinct absorption peak, for p-polarized light, at about 668 nm and its corresponding absorption profile 12 in Fig. 2(b) shows the strong localization of light around the silver core. All of them are the characteristics of LSPs. It is noticed that the p-polarized illumination is essential as a condition to excite surface plasmons. Both LSPs and Mie scattering will increase the optical path length and thus improve the photon absorption in active layers.

The core-radius tuneability of absorption in $\alpha$-Si SNSCs is further investigated. The radius of SNSCs is fixed at 150 nm, while the radius of silver-wire core is varied from 5 to 90 nm. In Figs. 3(a)-3(c), two-dimensional contour maps of absorption enhancement are plotted as a function of illumination wavelength and core radius. The colormap is in logarithmic scale to show the lower value more clearly. Figures 3(a) and 3(b) correspond to the illumination of s-polarized and p-polarized, respectively. As shown in Fig. 3(a), a series of extremely high peaks are observed near 790 nm for larger radii of silver core, whose enhancement factor can reach up to 65. The absorption maxima are mostly located at near-infrared region where the absorption ability in $\alpha$-Si is quite weak. Such an enhanced absorption at band-edge is favorable for solar cells.

![Fig. 3. Contour map of $Q_{abs}$ enhancement in SNSCs as a function of illumination wavelength and core radius for (a) s-polarized and (b) p-polarized. (c) The short-circuit current enhancement as a function of radius. The radius of $\alpha$-Si SNSCs, $R$, is fixed at 150 nm.](image-url)

To evaluate the overall absorption across the solar spectrum matched for $\alpha$-Si, the photocurrents are calculated in $\alpha$-Si SNSCs ($R = 150$ nm) with different core radii. The obtained results are then compared with the photocurrent produced by the reference cell—a $\alpha$-Si SNSCs ($R = 150$ nm) without core. The enhancement factor as a function of core radius is shown in Fig. 3(c). When an Ag core of 55 nm in radius is integrated into the SNSCs, the
absorber is only 95 nm remaining in thickness, but it experiences a 15.6% enhancement in the photocurrent than the reference cell, of which the absorber is 150 nm in radius. If the volume of absorber is considered, the enhancement is far more than this. For example, with the core radii of 55 nm and 60 nm, as shown in Fig. 3(c), the photocurrent enhancement per volume in the α-Si SNSCs can reach up to 34% and 36%, respectively.

It is also clearly shown in Fig. 3(a) that the absorption maxima tend to redshift with decreasing radius as both the LSPs and Mie scattering depend on the core size parameters [23,26]. The red or blue shift of absorption maxima is determined by surface plasmon resonances and Mie scattering by silver core. Decreasing the core size leads to the surface plasmon band and the scattering peak red shift, and then leads to the absorption maxima red shift. To demonstrate the physics in detail, the scattering theory, which can describe the optics behavior of both Mie scattering and surface plasmon resonances, is employed to study the shift of resonance peaks. Here, take the case of p-polarized illumination as an example, which is the same as the case of s-polarized illumination, to explain the shift of scattering peaks. According to the scattering theory [23,27], the scattering cross sections, $C_{\text{scat}}$, of silver core in the concerned system can be obtained from the polarizability,

$$C_{\text{scat}} = \frac{(2\pi)^4}{6\pi\varepsilon_0^2\lambda^4} |\alpha|^2$$

$$= \frac{128\pi^5 r^6}{3\lambda^4} \left\{ \frac{(e_{aSi} - 1)(e_{Ag} + e_{aSi})}{(e_{Ag} - e_{aSi})(e_{aSi} - 1)R^2} \right\}^2$$

$$+ \frac{2(e_{Ag} - e_{aSi})r^2R^2 \cos 2\phi}{[(e_{Ag} - e_{aSi})(e_{aSi} - 1)r^2 + (e_{Ag} + e_{aSi})(e_{aSi} + 1)R^2]^2}$$

$$+ \frac{2(e_{Ag} - e_{aSi})r^2R^2 \sin 2\phi}{[(e_{Ag} - e_{aSi})(e_{aSi} - 1)r^2 + (e_{Ag} + e_{aSi})(e_{aSi} + 1)R^2]^2}. \quad (3)$$

where $\alpha$ is the polarizability, $\phi$ is the incident angle in x-y plane, $\vec{r}$ is the space vector in the radial direction, $e_{Ag}$ and $e_{aSi}$ are the dielectric functions of silver and amorphous silicon, respectively. Without loss of generality, we set $\phi = 0$, $\vec{r} = r$ and $\beta = r/R$ ($R =$ constant, e.g., 150 nm as the discussion above), then Eq. (3) can be rewritten as following,

$$C_{\text{scat}} = C_{\text{scat}}(\lambda, \beta) = \frac{128\pi^5 R^6 \beta^6}{3\lambda^4} \times$$

$$\left\{ \frac{(e_{aSi} - 1)(e_{Ag} + e_{aSi})}{(e_{Ag} - e_{aSi})(e_{aSi} - 1)} \right\}^2 + \frac{2(e_{Ag} - e_{aSi})R^2 \cos 2\phi}{\left\{[(e_{Ag} - e_{aSi})(e_{aSi} - 1)r^2 + (e_{Ag} + e_{aSi})(e_{aSi} + 1)R^2]^2\right\}^2}. \quad (4)$$

As shown in Eq. (4), the scattering cross section, $C_{\text{scat}}$, changes as a function of $\lambda$ and $\beta$. To find the resonance peaks, the normalized scattering cross section is plotted in Fig. 4 against the illumination wavelength $\lambda$ and $\beta$. As shown in Fig. 4, it is obvious that the position of the scattering peak redshifts as the core size $r$, which is proportional to $\beta$, decreasing. Such unique characteristics enable a continuous tuning of the absorption maxima in solar cells by controlling the size of the silver core embedded in the SNSCs. Similarly, if the $R$ increases while the $r$ is fixed, the scattering peak will be expected to blueshift.
3.2 Influence of the core on photon absorption for SNSCs with varying radius $R$

Figure 5 shows the influence of the core on the absorption in SNSCs with varying radius for p-polarized light. Figures 5(a) and 5(c) describe the absorption efficiency of SNSCs without silver core, while Figs. 5(b) and 5(d) describe that of SNSCs with silver core. The core radius is chosen as 55 nm, and the nanowire radius, $R$, is changing from 100 to 250 nm. The colormap is in logarithmic scale to show the lower values more clearly. The points 1, 2, and 3 in Fig. 5(a) are corresponding to the absorption peaks 1, 2, and 3 in Fig. 5(c), respectively; the points 1', 2', and 3' in Fig. 5(b) are corresponding to the absorption peaks 1', 2', and 3' in Fig. 5(d), respectively. The points 1 in Fig. 5(a) and 1' in Fig. 5(b) are corresponding to the same radius of 240 nm; the points 2 and 2', the same radius of 160 nm; the points 3 and 3', the same radius of 130 nm. For convenience, the insets beside points 1', 2', and 3' in Fig. 5(b) are named by Inset 1', 2', and 3' respectively.

It can be concluded from Fig. 5(a) that LMRs actually exist in the $\alpha$-Si SNSCs without core and the resonance wavelengths tend to blueshift as the radius of SNSCs decreasing. As shown in Fig. 5(a), there are series of absorption peaks in the three directions pointed by arrows. Each series shares the same optical resonance mode as shown in Inset L1, L2, and L3, which are the known LMRs [15]. With similar wavelengths, the absorption enhancement in nanowires with different radius values may originate from completely different resonances. To exemplify this, the $Q_{abs}$ spectra of nanowires with the radii of 240 nm (point 1), 160 nm (point 2), and 130 nm (point 3) are plotted in Fig. 5(c). As shown in Fig. 5(c), the resonance peaks are close to each other but belong to different LMRs as shown in Insets L-1, L-2, and L-3. The insets are the normalized H-field distribution, whose intensities are amplified to show the steady mode clearly.

From Fig. 5(b), it can be concluded that LSPs are excited under p-polarized illumination while the core is embedded in SNSCs, and account for the main contribution to the photon absorption. Compared with LSPs caused by the silver core in SNSCs, the LMRs do exist but are weak. As shown in Fig. 5(b), the absorption profile in Insets 1' and 2' are similar (but distorted) to that in their corresponding Insets L1 and L2. This indicates that the leaky modes are coupled into LSPs, for larger radii, e.g., 240 nm (point 1') and 160 nm (point 2'). For smaller radius, e.g., 130 nm, as shown in Inset 3', there is no sign of leaky mode at the absorption peak 3', which indicates that LSPs are the only contributor to photon absorption.

As shown in Figs. 5(c) and 5(d), the peaks of LMRs corresponding to the peaks 1, 2, and 3 in Fig. 5(c) cannot be seeked out in Fig. 5(d). This also suggests that the LMRs in SNSCs
with $R$ of 240 nm, 160 nm and 130 nm are coupled into LSPs or disappeared after the silver core is embedded. As shown in Figs. 5(c) and 5(d), with silver core, the SNSCs absorb much more light at the resonance wavelength than that without, and the resonance wavelength tend to blueshift compared to that of LMRs. As shown in Fig. 5(d), the resonance wavelength of peaks 1' shifts from 696 to 668 nm compared to the corresponding peak 1 in Fig. 5(c); the resonance wavelength of the peaks 2' shifts from 704 to 688 nm compared to the peak 2 in Fig. 5(c). With the decrease of the radius of SNSCs, both the LSPs and LMRs tend to blueshift.

Figure 5 shows the influence of the core, for s-polarized light, on the photon absorption in the SNSCs with varying radius. Figures 6(a) and 6(c) depict the absorption efficiency of SNSCs without silver core, while Figs. 6(b) and 6(d) depict that with core. As shown in Figs. 6(a) and 6(b), LMRs, like that in Fig. 5(a), are observed clearly not only in the SNSCs without core but also in that with core. In addition, the embedded silver core will not affect the resonance wavelengths of LMRs. To further demonstrate this characteristic, the line plots of $Q_{abs}$ spectra in the SNSCs with and without core are plotted in Figs. 6(d) and 6(c) respectively. To facilitate comparison, the radius values of SNSCs are chosen the same as above: 240 nm, 160 nm, and 130 nm. As shown in Figs. 6(c) and 6(d), the peaks 1-4 are corresponding to the peaks 1'-4', respectively. As shown in Fig. 6(c), for $R$ of 160 nm, the LMRs are too low to make out or they are not existed; for $R$ of 240 nm and 130 nm, the resonance wavelength of LMRs are 697 nm (peak 1) and 703 nm (peak 3) respectively. And it is noted that the peaks 4 and 2 do not belong to LMRs. As shown in Fig. 6(d), after the core is embedded in the SNSCs, the LMRs are still existed and the resonance wavelengths are as the same as before. For some non-LMRs peaks, such as the peaks 2 and 4, the silver core will not affect their peak position so much too. The absorption enhancement for peak 4' corresponding $R$ of 130 nm is due to the Mie scattering and the decrease in absorption spectra between peak 3' and peak 4' is due to the reduction of volume.
Fig. 6. Contour maps of $Q_{abs}$ in the SNSCs (a) without and (b) with silver core versus the wavelength and radius of SNSCs, $R$. The absorption efficiency in the SNSCs (c) without and (d) with silver core as a function of radius of SNSCs, $R$. The core radius, $r$, is 55 nm and the incident plane wave is considered as s-polarized light. Insets: E-field distribution in SNSCs.

From the investigation on the interaction of LMRs with Mie scattering and LSPs, it can be concluded that LMRs and Mie scattering have little effect on each other, and therefore most of LMRs are existed and are keeping the resonance wavelength unchanged after the silver core is embedded into SNSCs; on the contrary, LMRs are affected strongly by LSPs, resulting in coupling into LSPs or being disappeared after the core is embedded.

The absorption enhancement caused by the silver core is wavelength dependent, under both s- and p-polarized illumination; therefore, the absorption has been integrated to obtain the photocurrent under AM 1.5G solar irradiance. The photocurrent produced by the SNSCs with silver core is divided by that without core to demonstrate the current enhancement caused by the silver core. As shown in Fig. 7, there are two peaks corresponding to the radii of 150 and 230 nm and the better one is 150 nm, which is consistent with the above calculation. The results also hint that there is only one solution of combination of $r$ and $R$ to get the highest current enhancement for the SNSCs with moderate radius values.

Fig. 7. The short-circuit current enhancement as a function of radius of SNSC, $R$. The core radius, $r$, is fixed at 55 nm.
3.3 Optimization and evaluation

To further investigate the optimal combination of core size \( r \) and nanowire radius \( R \), the contour maps of current enhancement versus filling ratio and \( R \) are plotted in Fig. 8. The benefit of the silver core for solar cells can be determined by comparing the current in \( \alpha \)-Si absorber layer with the counterpart without core. The filling ratio \( \eta \) is defined as \( r^2/R^2 \), which is equal to the volume ratio of the metallic core to the whole solar cell. Moderate radius values from 100 nm to 190 nm are considered, as the greater radius is unprofitable for carrier collection.

As shown in Fig. 8, ridge-like peaks of current enhancement are clearly observed in surface plot for s-, p-, and non-polarized illumination. The isolines are approximately straight in most parts of the contour maps.

![Fig. 8. Surface and contour plot of current enhancement versus filling ratio and radius of nanowire under illumination of (a) s-polarized, (b) p-polarized and (c) non-polarized light.](image)

Fig. 8. Surface and contour plot of current enhancement versus filling ratio and radius of nanowire under illumination of (a) s-polarized, (b) p-polarized and (c) non-polarized light.

![Fig. 9. Maximum of \( J_{sc} \) enhancement (square points in blue) and its optimum filling-ratio (circle points in red) as a function of radius of SNSCs. The light green line is the linear fitting for the relationship between \( \eta_{opt} \) and \( R \).](image)

Fig. 9. Maximum of \( J_{sc} \) enhancement (square points in blue) and its optimum filling-ratio (circle points in red) as a function of radius of SNSCs. The light green line is the linear fitting for the relationship between \( \eta_{opt} \) and \( R \).

To illustrate more clearly, the ridge-like current peaks in Fig. 8 are extracted and plotted in Fig. 9. Meanwhile, its corresponding optimum filling-ratio as a function of radius of SNSCs is also described in the same figure. As shown in Fig. 9, with increasing \( R \), the maximum \( J_{sc} \) enhancement rises first and then falls slightly; the summit with 16.6% enhancement is corresponding to the filling-ratio of 7.84% and the nanowire radius of 130 nm. Therefore the optimum combination for \( r \) and \( R \) is that \( r = 36 \) nm and \( R = 130 \) nm. As shown in Fig. 9, it is clear that different \( R \) correspond to different optimal filling-ratio \( \eta \), and that when the \( R \) become greater the optimal filling-ratio \( \eta_{opt} \) is increasing linearly, as given by
\[ \eta_{\text{opt}} = \frac{r^2}{R^2} = k \cdot R + b. \quad (5) \]

and then, \[ r = \sqrt{k \cdot R + b \cdot R}. \quad (6) \]

where \( k \) is the slope coefficient, \( b \) is the intercept of fitting-line, which both can be calculated by numerical fitting from Fig. 9. Once the \( k \), \( b \), and \( R \) are determined, the \( r \) can be solved from Eq. (6). For natural non-polarized light, if \( R \) is in units of micrometers, then \( k = 3.0 \) and \( b = -0.307 \).

4. Conclusion

In conclusion, we proposed and investigated numerically that how the silver core could be utilized to modulate the photon absorption and thus photocurrent in single nanowire solar cells. Firstly, we investigated the influence of silver cores in the specific SNSCs where no LMRs existed, and found that LSPs and Mie scattering were excited and resulted in a great enhancement in photon absorption. Next, we adjusted the radius of SNSCs to generate LMRs and then explored how the LSPs and Mie scattering interacted with LMRs. The results suggested that most of LMRs would couple into LSPs or be disappeared under p-polarized illumination and would not be affected so much by Mie scattering under s-polarization; the contributors to light trapping were demonstrated to be mainly LSPs, and then Mie scattering and LMRs. By toning the core size \( r \), and radius of SNSCs, \( R \), we found that the resonances of LSPs tended to redshift as the core radius decreasing, and that the resonances of LSPs and LMRs tended to blueshift as the \( R \) decreasing. Finally, the optimal combination of core radius and radius of SNSCs was calculated from the linear relationship between the optimum filling-ratio and the radius of SNSCs, and an enhancement of 16.6% in photocurrent was produced by SNSCs with nanowire radius of 130 nm and core radius of 36 nm.

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