Ag nanoparticles-embedded surface plasmonic InGaN-based solar cells via scattering and localized field enhancement

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Abstract: Ag nanoparticles are embedded in intentionally etched micro-circle p-GaN holes by means of a thermal agglomeration process to enhance the light absorption efficiency in InGaN/GaN multi-quantum-well (MQW) solar cells. The Ag nanoparticles are theoretically and experimentally verified to generate the plasmon light scattering and the localized field enhancement near the MQW absorption layer. The external quantum efficiency enhancement at a target wavelength region is demonstrated by matching the plasmon resonance of Ag nanoparticles, resulting in a Jsc improvement of 9.1%. Furthermore, the Ag-nanoparticle-embedded InGaN solar cell is effectively fabricated considering the carrier extraction that more than 70% of F.F. and 2.2 V of high Voc are simultaneously attained.

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well (MQW) structure including the absorption layer of a high crystalline quality and a high spectrum [7]. At present, most InGaN-based solar cells adopt an InGaN/GaN multi-quantum-content InGaN absorption layer is required to absorb a longer wavelength region in the solar spectrum [1–5]. In addition, InGaN has been a promising material for solar cell applications due to its good optical, electrical properties, and a tunable bandgap energy ranging from 0.7 eV (InN) to 3.4 eV (GaN) which can nearly cover the entire range of the solar spectrum [1–5]. In addition, InGaN shows higher resistance to proton irradiation than Si or other III-V materials such as GaAs and GaInP mainly applicable for space-based solar cells without the performance degradation [6].

To obtain high conversion efficiency in the InGaN-based solar cells, a high-indium (In)-content InGaN absorption layer is required to absorb a longer wavelength region in the solar spectrum [7]. At present, most InGaN-based solar cells adopt an InGaN/GaN multi-quantum-well (MQW) structure including the absorption layer of a high crystalline quality and a high performance.
In composition [8–11]. However, it is difficult to absorb all of the incident photons because the thickness of the absorption layer in the InGaN/GaN MQWs is limited to only dozens of nanometers [3, 8, 12]. Furthermore, the absorption coefficient of InGaN is smaller for a longer wavelength incident light, which leads to a reduced external quantum efficiency in the region of longer wavelength, consequently resulting in a limited power conversion efficiency [10, 13].

To increase the light absorption efficiency of a solar cell having a thin absorption layer, there have been many efforts to employ plasmonic nanoparticles because they can generate the light scattering and the strong electro-magnetic field localization near the nanoparticles confine the incident light by increasing the optical path length [14–17]. One method to form a plasmonic solar cell structure is to embed nanoparticles of the subwavelength scale of the incident light, within the absorption layer in order to maximize plasmonic coupling and trap the light [15]. It is relatively easy to insert metal nanoparticles in organic materials by blending nanoparticles with a thin active absorbing layer or using layer-by-layer spin coating that many previous studies already reported in organic-based plasmonic solar cell [18–22]. In contrast, it is challenging to insert metal nanoparticles in the absorbing layer of inorganic-based solar cells such as Si or III-V compounds semiconductors because it is required to coat aggregation-free-metal nanoparticles on the wafer and continuously grow a subsequent high quality film on the top. The typical GaN growth temperature (~1000°C) is similar or even higher than melting point of metal nanoparticles so that it causes metal out-diffusion and incorporation problem during the following GaN layer growth, resulting in the poor crystal quality of epitaxial layers. Defects or impurities originated from the poor epitaxial layer promote carrier recombination, so that degrade electrical characteristics in a solar cell such as short circuit current density and open circuit voltage. Therefore, the metal nanoparticles are commonly located on the top of the solar cell surface to enhance external quantum efficiency by increasing plasmonic scattering in inorganic-based solar cell [23–26].

Of these, Pryce et al. first used Ag nanoparticles as a surface plasmon resonator in InGaN-based solar cells [15]. They located Ag nanoparticles on the top p-GaN surface and observed plasmonic effect varying the p-GaN thickness. In the case of a 200 nm thick conventional p-GaN layer, plasmonic field generated near the Ag nanoparticles cannot influence to the active InGaN/GaN MQW absorption layer because it completely decayed while penetrating the 200 nm thick p-GaN. In the case of relatively thin p-GaN (~50 nm) layer, plasmonic interaction between the nanoparticles and the InGaN/GaN MQW absorption layer occurred by reducing the distance, however, carrier collection efficiency is deteriorated due to insufficient current spreading of resistive thin p-GaN (~50nm), resulting in degradation of solar cell performance.

For the plasmonic local field enhancement, Wang et al. simulated plasmon interaction by modelling Ag nanoparticles embedded in an intrinsic-InGaN absorption layer and numerically demonstrated that its efficiency can be enhanced by up to 27% compared to the conventional structure without nanoparticles [27]. Nevertheless, the simulation results have not been experimentally proved due to the degradation problem of the epitaxial InGaN layer containing the nanoparticle as we mentioned above. Therefore, a novel method is required to insert metal nanoparticle near the MQWs absorption layer to form strong localized field maintaining conventional p-GaN thickness (~200 nm) for carrier extraction.

Not only the local field enhancement but also the scattering has to be also considered in nanoparticle embedded plasmonic solar cell. The incident light is scattered in all direction near the nanoparticle that control the directionality of scattered light has an effect on absorption efficiency of solar cell. The ratio of forward to backward scattering determines the effectively incident light power and scattered angle changes optical path length in absorption layer of the solar cell.

In this study, we insert the plasmonic Ag nanoparticles only in micro-patterned region which has close distance from the absorption layer to overcome aforementioned issues. We intentionally pattern micro circle areas and etch p-GaN holes. Then, the hemispherical Ag
nanoparticles are embedded in the etched circle regions for strong plasmonic interaction between the nanoparticles and the absorption layer which has only ~20 nm distance. Furthermore, relatively thick non-etched regions excluding the Ag nanoparticles acts as a current spreading path and efficiently extract generated carriers from light absorption. We verified that the embedded plasmonic Ag nanoparticles considerably enhance light absorption efficiency without any performance degradation in solar cell. This is the first experimental demonstration of plasmonic metal nanoparticle embedded InGaN-based solar cell. We compare the performance of the solar cells including the Ag nanoparticles and that of the conventional structure for clear evidence. We also theoretically demonstrate the role of the Ag nanoparticles in the plasmonic InGaN solar cell by analyzing the plasmonic scattering effect and the localized field enhancement in detail. We tried to study size effect of plasmonic metal nanoparticle on light absorption efficiency in solar cell by comparing the dominant effect between scattering and localized field enhancement which depends on the size of the nanoparticle.

2. Experiments

The InGaN-based solar cells were grown on sapphire substrates by using a metal-organic chemical vapor deposition (MOCVD) system. The solar cell structure consists of a 2 μm thick Si-doped n-GaN layer, seven periods of In0.17Ga0.83N/GaN (3 nm/ 5 nm) MQW absorption layer, and a 200 nm thick Mg-doped p-GaN top layer. The target light absorption region was estimated to be occurred below ~460 nm, considering bandgap energy (2.7 eV) of the In0.17Ga0.83N/GaN MQW. Using this structure, we embedded Ag nanoparticles near the MQW absorbing layer and fabricated surface plasmonic solar cells (SP-SC) as shown in Fig. 1. At first, we deposited a 500 nm thick SiO2 layer for an etching mask and mesa etch was done until n-GaN was exposed using an inductive coupled plasma (ICP) etching system. Even after we etched by 500 nm deep to form a mesa region, ~300 nm thick SiO2 mask layer was still remained due to the high etching selectivity between SiO2 and GaN. On this structure, we patterned micro circles with a 2 μm diameter and 4 μm periods using a photoresist (PR) mask. Then, we etched a micro-circle-patterned region in the order of SiO2 and p-GaN layer, remaining only ~20 nm deep p-GaN holes, by a reactive ion etching (RIE) system followed by ICP. An Ag film was deposited on this structure and the remaining SiO2 sacrificial layer (300 nm) was subsequently removed in a hydrogen fluoride (HF) solution so that the thin Ag film existed only in the etched micro-circle regions. This template was annealed in a rapid thermal annealing machine under a nitrogen (N2) atmosphere at 600 °C for 5 min in order to form Ag nanoparticles from the thin Ag film. Three different thicknesses of the Ag film were attempted to examine the morphology of the resulting Ag nanoparticles for better extinction efficiency. Finally, a 200 nm thick indium tin oxide (ITO) layer was deposited as a current spreading layer and Cr/Au (30 nm/ 300 nm) metal pads were formed for n- and p-type contacts. For clear comparison, another conventional solar cell (SC) having the same micro pattern without the Ag nanoparticles was fabricated simultaneously.

Figure 1 shows the fabrication process flow of conventional SC and Ag nanoparticles embedded SP-SC. SEM images are cross-sectional view displaying the patterned p-GaN of SC and SP-SC, respectively. As shown in SEM images, micro holes in the p-GaN with 2 μm diameter and 4 μm periods were uniformly patterned and an etch depth was 180 nm. The distance from etched micro-hole to MQW is 20 nm for both samples. The SP-SC sample represents the Ag nanoparticles embedded only in the micro p-GaN hole. The etched micro-hole region with 20 nm of p-GaN thickness was intended for light absorption enhancement by localized electric field enhancement near the MQW absorption layer, while the non-etched region having a much thicker p-GaN of 200 nm plays a major role as current spreading paths for efficient carrier extraction. The shape of nanoparticles in the etched hole was nearly hemispherical and their average size was ~75 nm when a 10 nm thick Ag film was thermally annealed. The Ag nanoparticles diameter of 75 nm utilized for the SP-SC were carefully
chosen to match the plasmon wavelength of Ag nanoparticles with the InGaN/GaN MQW absorption layer. In the plamonic solar cell, powerful light absorption enhancement is anticipated by strong plasmonic interaction. Therefore it is important to match the plasmon wavelength of metal nanoparticles with solar cell absorption wavelength. Plasmon resonance wavelength can be changed by size and shape of metal nanoparticles. And their size and shape can be controlled by some factors such as film thickness, annealing temperature and time [28].

Here in, we vary the size of Ag nanoparticles and observed their extinction efficiency including peak wavelength shift using ultraviolet-visible (UV-VIS) absorption spectrophotometer. And then we embedded optimized size of Ag nanoparticles in SP-SC for strong plasmonic effect. We theoretically analysed plasmonic scattering efficiency, scattering directionality and the amount of localized field enhancement varying the size of Ag nanoparticles. Hemispherical shaped-nanoparticles located between ITO and p-GaN/MQW, having the identical structure of fabricated SC-SP, is used for the exact simulation. Solar cell characteristics such as current-voltage (I-V) characteristic and external quantum efficiency (EQE) are measured by Oriel class AAA solar simulator under AM 1.5 G and incident photon-to-current efficiency (IPCE) measurement system, respectively.

3. Results and discussion

Figure 2 shows the SEM images and extinction efficiency spectra obtained from the three different Ag film thicknesses of 5, 10, and 15 nm. The upper row of Figs. 2(a)-2(c) shows top view SEM images of as-deposited thin Ag films in the etched micro-hole region. Those films are subsequently annealed at 600 °C for 5 min under N₂ ambient condition to form nanoparticles as shown in the lower row of Figs. 2(a)-2(c). During the thermal annealing, the Ag is agglomerated to lower the total energy of the system consisting of the Ag film and the substrate, resulting in separated three dimensional Ag nanoparticles [29–31]. In the case of annealing of 5 nm and 10 nm thick Ag film, hemispherical nanoparticles are formed, while mesh-like nanoparticles are formed from the 15 nm thick Ag film presumably due to coalescence of relatively large amount of Ag. As the initial Ag film thickness increases the
Ag nanoparticle dimension also increases. It is additionally observed that shape and size of nanoparticle become more irregular as increasing Ag film thickness. Figure 2(d) illustrates the extinction efficiency measured from the all the as-deposited and annealed Ag films using an UV-VIS spectrometer. The extinction efficiency is an important factor to determine the plasmon resonance wavelength because it is defined by the sum of the absorption and scattering efficiency [31]. In Fig. 2(d), minimum extinction at 320 nm corresponds to the wavelength which the real and imaginary parts of the dielectric function of Ag almost vanished and it is evidently observed for all the as-deposited and annealed Ag films. In the as-deposited Ag film samples (dotted lines), the extinction spectra are very broad and not clearly distinguished from the plasmonic resonance. In all the annealed samples having Ag nanoparticles (solid lines), however, main resonance peaks known as dipolar excitation mode are observed due to their specific nano-geometry at the wavelength ranging from 450 nm to 550 nm [32]. In particular, a relatively small peak near the ~350 nm which is called quadrupole resonance peak is obviously observed in the annealed Ag films of 10 nm and 15 nm. This quadrupole peak appears when quadrupole polarizability becomes important to extinction like that case of large size of nanoparticles. The interesting point is that main resonance peak caused by dipole extinction is red-shifted as the Ag nanoparticle size increases due to additional electromagnetic effects [33]. It signifies that the plasmonic resonance wavelength can be controlled by varying the Ag thickness and annealing condition. In addition, the main resonance peak becomes broader as the annealed Ag film thickness is increased. The broadening of extinction peak at resonance wavelength is expected by the result of sum of dipole and quadrupole extinction mode which have different resonance wavelength each other. Reduced local electromagnetic fields coupling between the nanoparticles due to irregular shape and size of nanoparticles, having various resonance peaks by themselves, can also broaden the resonance peak clearly seen in the annealed 15 nm Ag film. The reason of high extinction efficiency observed in nanoparticles formed by thick Ag film is that scattering appearing at broad wavelength region rapidly increases as increasing the radius of nanoparticle. This enhanced scattering at broad wavelength region takes the greater part of total extinction. Nevertheless, Ag nanoparticles formed by 10 nm Ag film show sharp and the strongest extinction peak at main resonance wavelength region. We expect that more regular shape of nanoparticles annealed by 10 nm Ag film than 15 nm results in relatively sharp peak. Moreover, absorption and scattering rate are well balanced that highest extinction peak is observed. In the case of Ag nanoparticles formed by 5 nm film it shows sharpest resonance peak, however, small sized nanoparticle result in lowest extinction efficiency due to small scattering rate. This will be further discussed with simulation result later in detail. Therefore, Ag nanoparticles obtained from the 10 nm Ag film are employed for device fabrication to match plasmonic resonance of Ag nanoparticle with the MQW’s absorption wavelength region below ~460 nm because they show the strongest and relatively narrow extinction efficiency near 450 nm.
Fig. 2. SEM images of Ag films and their extinction efficiency spectra with respect to the Ag thickness. SEM images of as-deposited (upper row of a, b, and c) and annealed (lower row of a, b, and c) Ag films with the thickness of 5 nm (a), 10 nm (b), and 15 nm (c). (d) Extinction efficiency spectra of all as-deposited and annealed Ag films measured by an UV-VIS spectrometer.

Figure 3(a) shows current density–voltage (J-V) characteristics of the SP-SC and the SC under dark and air mass 1.5 (AM 1.5) illumination conditions. The important solar cell parameters are measured and summarized in Table 1. The notable difference is the enhanced short circuit current density ($J_{sc}$) of up to 9.1% in the SP-SC compared to the SC due to the increased light absorption at the MQW region. To investigate the $J_{sc}$ difference more clearly in terms of plasmonic effect depending on its resonance wavelength, we scrutinize external quantum efficiency (EQE) by varying the incident wavelength as shown in Fig. 3(b). EQE difference defined as the EQE value of SP-SC minus EQE value of SC is also plotted.

It is worthy to note that the EQE difference shows a considerably similar shape to the extinction efficiency spectrum of Ag nanoparticles obtained by annealing of a 10 nm thick Ag film shown in Fig. 2(d). However, the EQE difference spectra are slightly blue-shifted by including the Ag nanoparticles with an ITO layer. Major EQE difference in the SP-SC is
observed within the 400 - 460 nm range corresponding to main resonance peak of the Ag nanoparticles and the highest EQE difference is measured by 6.7% at ~420 nm. At this 420 nm of wavelength, the EQE enhancement factor was calculated by 39% (EQE of SP-SC divided by EQE of SC) which is the higher value than $J_{sc}$ improvement. Strong plasmonic interaction between the Ag nanoparticles and the MQW absorption layer enhances the EQE at the target wavelength region (near the band edge of the InGaN/GaN MQWs), resulting in $J_{sc}$ improvement. Moreover, it should be pointed out that the nanoparticle size and the micro-circle areas are yet to be further optimized for even higher EQE enhancement. Slightly reduced open circuit voltage ($V_{oc}$) is observed in the SP-SC. It is due most likely to the surface defects originated from the interface between Ag nanoparticles and GaN which may cause carrier recombination center. However, it does not seem to seriously influence the solar cell performance compared to SC [27]. We expect that metal agglomeration process improved the interface between nanoparticle and GaN. The annealing process of the ITO layer also improved the interface between nanoparticle and ITO that surface defects and carrier recombination could be diminished. In our SP-SC, the non-etched region acts as an efficient current spreading path contributing to obtain over 70% of reliable fill factor (F.F.) and enhancement of $J_{sc}$ is possible at the same time by virtue of the plasmonic effect, which results in 6.5% improvement of the power conversion efficiency compared to the SC.

Fig. 3. Current density-voltage characteristic and external quantum efficiency. (a) Current density-voltage characteristics of SC and SP-SC under dark and illumination condition. (b) External quantum efficiency and EQE difference of SC and SP-SC.

| Table 1. Solar cell performance parameters of SC and SP-SC |
|-----------------|-----------------|-----------------|
| $V_{oc}$ (V)    | 2.24            | 2.20            |
| $J_{sc}$ (mA/cm$^2$) | 0.66            | 0.72            |
| F.F. (%)        | 73.3            | 72.7            |
| Efficiency (%)  | 1.08            | 1.15            |

It is crucial to further clarify which plasmonic effects occur in our structure and what specific mechanism contributes to light absorption efficiency enhancement at active MQWs region. So that we perform simulations considering hemisphere shaped Ag nanoparticles. At first, we estimate the average size of the Ag nanoparticles formed by annealing the 10 nm thick Ag film using the image processor (Image J) as displayed in Fig. 4(a) [28]. Although most of nanoparticles are distributed near ~75 nm of the average diameter, the size of nanoparticle broadly spreads from 20 nm to 160 nm. We mainly simulate plasmonic effect with the Ag nanoparticles of 75 nm diameter embedded in our SP-SC. In addition, we
investigate 20 nm and 160 nm corresponding to minimum and maximum size of nanoparticle from the distribution diagram, to evaluate size dependence on plasmonic effect for solar cell.

For the simulations, we utilize a three-dimensional wave optics model in COMSOL Multiphysics, which supports a finite element method (FEM). Extinction cross-section, scattering amplitude, scattering directionality and localized electric fields are confirmed out. The wavelength range is varied from 300 nm to 500 nm at 10 nm intervals. Ag is assumed to have a complex-valued permittivity with the Lorentz-Drude model. The refractive indices for the ITO and the GaN layers are set to be 2 and 2.53, respectively.

The z-direction polarized light is illuminated to ITO/Ag nanoparticle/p-GaN/MQWs structure and propagated toward x-direction with the light intensity of 1 MW/m², as shown in Fig. 4 (b). Figures 4(c)-4(e) represent simulated extinction cross-section, scattering cross-section, and absorption cross-section with respect to the Ag nanoparticle diameter of 20 nm, 75 nm, and 160 nm. For all cases, the extinction cross-section increases as the Ag nanoparticle diameter becomes enlarged. However, dominant contribution to extinction between scattering and absorption differs according to the size of nanoparticles. The smaller size nanoparticles mostly effect on the absorption and the larger size nanoparticles dominantly effect on the scattering. As the diameter of the nanoparticles is increased, the ratio of the scattering to the absorption cross-section is also increased. In our structure, the nanoparticles are located on p-GaN, which is ~20 nm of distance from MQW region. If the rate of forward scattering is higher than backward scattering, it is beneficial for increasing the incident sunlight power at the active MQW region.

![Fig. 4. (a) Distribution of Ag nanoparticles formed by annealing of a 10 nm thick Ag film. (b) simulation structure of extinction cross section. Extinction cross section of (c) 20 nm, (d) 75 nm and (e) 160 nm diameter of Ag nanoparticles.](image)

Therefore, the scattering directionality is also estimated with the same schematics that we calculate the extinction cross-section. We consider the light illumination of 420 nm wavelength showing the highest EQE enhancement for simple calculation and data collection.
The scattering directionality is substantially important to enhance light absorption at the MQW region because the effective light absorption path is extended due to the inclined incident light which is usually scattered near the nanoparticle. Figures 5(a) and 5(b) show the scattering amplitude of Ag nanoparticle captured by x-y plane (a) and x-z plane (b) varying the nanoparticle diameter of 20 nm, 75 nm and 160 nm. In each figure, 0° angle indicates that the light propagates along x-direction. For all cases, the forward scattering amplitude is stronger than the backward scattering amplitude. Moreover, as the diameter of the nanoparticle increases, the forward scattering amplitude becomes stronger and the scattering angle also increases. The experimental results obtained above reveal that larger diameter of nanoparticles has more beneficial to enhance the light absorption at MQWs due to high forward scattering rate. Meanwhile, we also have to consider metal absorption, which extremely occurs in small size of nanoparticle, radiating electric field and forming localized electric field.

Therefore, the localized electric fields of the Ag nanoparticle are investigated assuming that the period is twice of the diameter of the Ag nanoparticle. The localized electric field is calculated under same condition of extinction cross-section and scattering amplitude. To observe and measure the electric field at the surface of MQW, we add a surface detector 20 nm below the interface between the ITO and the GaN layer. Figure 6 (a) illustrates the electric field distributions of the Ag nanoparticles of 75 nm diameter on y-z plane and y-x plane under 420 nm light illumination with the light intensity of 1MW/m². It is apparent that strong electric field is formed along y-axis and is positioned at the sharp corners of the nanoparticle as shown in x-y plane image. This large enhanced electric field at the sharp corners are called lighting-rod effects and it increases the light absorption efficiency by being strongly localized near the MQWs region. The y-z plane image shows the electrical field distribution at MQW absorbing layer caused by the Ag nanoparticle. The strengthened field intensities under the nanoparticle differ by their position. To obviously compare the nanoparticle size effect, we introduce the normalized electric field intensity by summing all of the field distribution at MQWs region. Figure 6(b) depicts the normalized electric field intensity at MQW region for varying Ag nanoparticle diameter and incident wavelength. Strong normalized electric fields are observed for all wavelengths when the diameter of the Ag nanoparticles is smaller than ~40 nm. However, localized electric field changes with respect to incident wavelength when the diameter of Ag nanoparticles is larger than ~40 nm. Therefore, determination of proper size of nanoparticle is required for forming strong localized field at the absorption layer under specific incident wavelength region.

Fig. 5. Polar plots of scattering amplitude of an Ag nanoparticle captured with (a) x-y plane and (b) x-z plane.
Fig. 6. (a) Electric field distributions of Ag nanoparticle of 75 nm diameter under 420 nm wavelength illumination captured on x-y plane and y-z plane, respectively. (b) normalized electric field intensity at the MQW region for varying wavelength and diameter of Ag nanoparticle.

It is conclusive that the embedded Ag nanoparticles employed in this study enhance the light absorption efficiency with plasmonic effect from two points of view. Small sized nanoparticles strengthens the localized electric field near the MQWs and large sized nanoparticles increase forward scattering, propagating scattered light toward the MQWs. Figure 7 shows the relationship between normalized electric field at MQWs, which effected by localized field enhancement, and scattering/absorption ratio. In other words, smaller size of nanoparticle than ~75 nm dominantly contributed to localized field enhancement and larger size of nanoparticle contributed to plasmonic scattering for solar cell operation as shown in Fig. 7. This experiment results obtained in this study indicate that embedment of plasmonic Ag nanoparticles near the absorption layer is viable even in inorganic based-solar cell without any growth problem or performance degradation of device. Further improvement of solar cell efficiency is expected by optimizing the area of etched-micro-hole region containing metal nanoparticles or forming uniform size of nanoparticles. In addition control the distance from nanoparticle to absorption layer considering diameter of nanoparticle and incident light wavelength is also required to utilize embedment of plasmonic nanoparticles in diverse opto-electronic devices on their purpose.
4. Conclusion

In conclusion, we have fabricated InGaN-based plasmonic solar cells to enhance the light absorption efficiency by embedding the Ag nanoparticles in the micro-patterned p-GaN hole regions. The Ag nanoparticles are theoretically and experimentally verified to generate plasmonic light scattering and localized field enhancement near the MQW absorbing layer. Small size of nanoparticle strengthens localized electric field near the MQWs while large size of nanoparticle increases forward plasmonic scattering. Although more optimization is required to maximize the absorption efficiency, we demonstrated EQE enhancement at a target wavelength region by matching the plasmon resonance of the Ag nanoparticles. Furthermore, Ag-nanoparticle-embedded SP-SC is effectively designed considering carrier extraction and well-fabricated accordingly so that more than 70% of F.F. and 9.1% of $J_{sc}$ improvement are simultaneously attained. This result implies that Ag nanoparticles embedded near the active absorption layer could be utilized in many other optoelectronic devices such as solar cells, photodetectors, and light-emitting diodes which require control of strong plasmonic resonance at a specific wavelength region with the reliable device operations.

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