LIGHT SCATTERING BY NOBLE METALLIC NANOPARTICLES FOR PERFORMANCE OF COMPOUND SOLAR CELLS ENHANCEMENT

NGUYEN DINH LAM[†]

Faculty of Physics Engineering and Nanotechnology,
VNU-University of Engineering and Technology, Vietnam National University,
144, Xuan Thuy, Cau Giay, Hanoi, Vietnam

E-mail: [†]lamnd2005@gmail.com

Abstract. *Light scattering by noble metallic nanoparticles is of interest for a variety of applications due to the large electromagnetic field enhancement that occurs in the vicinity of the metal surface, and the dependence of the resonance photon energy on the nanoparticle size, shape, local dielectric environment, and material. Here, the influences of electromagnetic scattering by Au and Ag nanoparticles placed atop compound solar cells on optical absorption and photocurrent generation were investigated based on the variation in the noble nanoparticle densities. The results indicated that the short-circuit current and power conversion efficiency were strongly affected by the density and material of the noble nanoparticles. The great improvement of 28% in power conversion efficiency can be obtained with Au nanoparticle density of 2×10^8 cm^{-2}. This improvement can be attributed to light scattering, light trapping, and surface roughness by noble nanoparticles. Furthermore, Au nanoparticles showed more efficient in solar cell power conversion efficiency improvement than Ag nanoparticles did although density of Au nanoparticle was lower than that of Ag nanoparticles.*

Keywords: Au nanoparticle; Ag nanoparticle; light scattering; surface roughness.

Classification numbers: 88.40.H-.

I. INTRODUCTION

Photovoltaic is emerging as an importance technology for the future of green energy production. To approach this potential, it will be necessary to reduce the manufacturing costs of photovoltaic cell while maintaining high working efficiencies. As potential routes to improving efficiency in photovoltaic devices generally, there is extensive interest in light trapping and manipulation techniques including antireflection coatings (ARCs), surface texturing, thin film solar cells and optical absorption enhancement via scattering from metallic or dielectric nanoparticles [1–9].

The use of scattering by metallic nanoparticles for light trapping in solar cell was a useful technique that based on excitation of surface plasmon resonances in metallic nanoparticles [6].

The surface plasmon resonance is a collected oscillation of the conduction electrons in the metal since excited by photon [5]. The plasmon resonance frequency of metallic nanoparticles depends on size, shape, particles material, and refractive index of the surrounding medium [10]. In practice, the plasmon resonance frequency will be reduced when the shape of nanoparticle losses their symmetric or dielectric function of surrounding increases [10, 11]. Furthermore, the density of free electron of silver and aluminum is highest leading to their surface plasmon resonance frequencies are also high (in ultra-violet region) and lower for gold and copper ones so surface plasmon resonance frequencies in visible region. Therefore, the plasmon resonance frequency depends on the material of particles. The plasmon resonance frequency of gold nanoparticles is lower than that of silver nanoparticles since the same deposited mass thickness [10].

In application for enhancement in optical absorption of solar cell, the short circuit current density or the power conversion efficiency are strongly influenced by the plasmon resonance frequency of metal nanoparticles that also depends on the size, shape, material, and surround medium of metallic nanoparticles. Keisuke Nakayama and et al. reported the influence of efficiency of thinner GaAs solar cell patterned with Ag nanoparticles fabricated by masked deposition through anodic aluminium oxide (AAO) templates on Ag density and shape. The strong scattering by the interacting surface plasmons and the increase of optical path of the incident light in the absorber layers attributed to resulting in an 8% increase in the short current density of the cell [8]. Besides that, 100 nm diameter Au nanoparticles (NPs) were deposited on the surface of In(Ga)As/GaAs quantum dot and InP/InGaAsP quantum well solar cells to investigate the surface plasmon resonance in Au NPs contribution. There was only an increase of 3% and 1% in the power conversion efficiency for quantum dot and quantum well solar cells, respectively, were observed [12, 13]. A small enhancement in the power conversion efficiency of this work may be due to 15nm thickness SiO_2 passivation layer that increases distance between particles and active region, resulting in a reduced fraction of the light was radiated into the cell [11]. For this reason, an enhancement of 25% in the power output, P_{max}, was obtained by using approximately 20 nm diameter Au nanoparticles directly deposited on the top surface of a-Si:H/c-Si heterojunction solar cell [14]. In this case, photocurrent response showed an increase of nearly all wavelength range even below resonance wavelength. Moreover, Au nanoparticles were directly deposited on the n-type doped a-Si:H site. Accordingly, besides of surface plasmon resonance, this result may be also attributed to the plasmon near-field coupling [9].

In this work, 30 nm in diameter of Au and Ag nanoparticles were directly deposited on top of the compound solar cells. Light scattering by these nanoparticles for the compound solar cells performance enhancement was also investigated based on the variation in density and type of material. Optical and electrical characteristics were utilized in this work for investigation.

II. MATERIALS AND METHODS

The schematic diagram of the compound solar cells that was used in this work was shown in Fig.1(a). In this study, 30 nm in diameter Au and Ag colloidal particles were implemented on the surface of cells by the spin coating method. The information and parameters of the samples were listed in Table 1.

Table 1. Notation and characteristics of the fabricated samples.

Samples	Density ($\times 10^8$ cm^{-2})	V_{oc} (V)	J_{sc}(mA/cm^2)	FF (%)	η(%)
Ref.	0	0.985	14.09	76.1	10.55
Ag$_1$	6	0.999	14.84	76.3	11.31
Ag$_2$	12	1.000	16.28	73.0	11.95
Ag$_3$	24	1.000	14.62	76.2	11.17
Au$_1$	0.5	0.998	14.45	75.9	10.95
Au$_2$	1	1.006	15.93	73.9	11.86
Au$_3$	2	1.012	18.06	73.7	13.48
Au$_4$	3	1.002	17.40	73.2	12.76

Devices were evaluated at room temperature in terms of their photocurrent response (I_{ph}) and illuminated current versus voltage (I-V) characteristics, both with and without nanoparticles on the top surface. Photocurrent measurement were performed using ORIEL® IQE 200^{TM} with 300W Xe lamp and illuminated I-V measurements were taken using a solar simulator with 150W Xe lamp, 1 sun air mass 1.5G. The reflectance and extinction spectra were measured using UV-Vis-NIR Cary 5000.

III. RESULTS AND DISCUSSION

Scanning electron micrograph (SEM) images of Au and Ag nanoparticles (NPs) deposited at typical concentrations of 2×10^8 and 12×10^8 cm^{-2}, respectively, were shown in Fig. 1(b) and Fig. 1(c). The Au NPs were present predominantly as isolated single particles. A few multiparticles clusters can be observed in this density of Au NPs. In contrary, more multiparticles clusters can be seen in the SEM image of Ag NPs because of its high density.
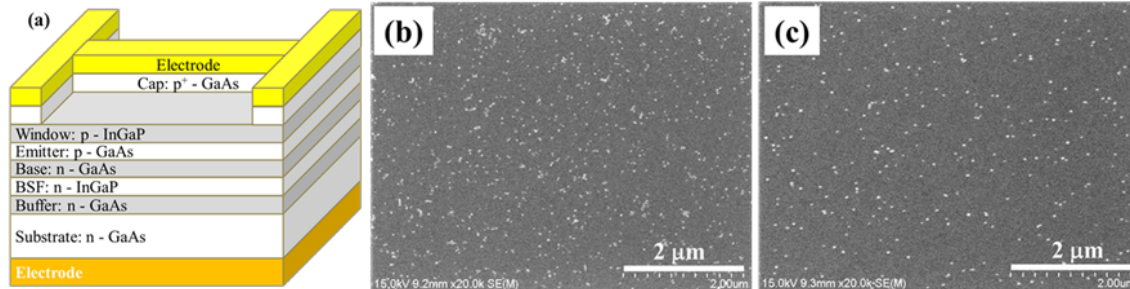

Fig. 1. (a) Schematic of the normal design compound solar cell. (b) Scanning electron microscope images of typical deposition results for Ag (left) and Ag (right) NPs, with density of 12×10^8 cm^{-2} and 2×10^8 cm^{-2}, respectively.

Extinction spectra for Ag and Au NPs densities of 12×10^8 and 2×10^8 cm^{-2}, respectively, deposited on glass substrates were shown in Fig. 2. The maxima in the extinction spectra were in consequence of destructive interference between scattered and incident field, corresponding to plasmon excitations in the Ag and Au NPs. Both types of particles were the same size but they exhibit different resonance photon energy scattering because of material dependence: around 2.25 eV and 2.80 eV for Au and Ag nanoparticles, respectively. Clusters of metal particles also reduce the transmitted field amplitude by reducing scattering compared to individual particles. Therefore, the observation of increase of extinction spectra over a broad range of photon energy from 1.8 eV to 2.25 eV can be attributed to clusters of Ag NPs. Moreover, the intensity of extinction peak of Ag NPs was higher than that of Au NPs. Thus electric field radiation was higher as NPs density was higher [8].
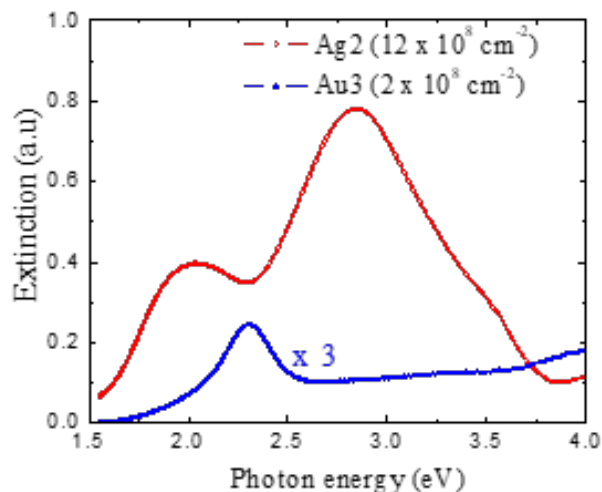

Fig. 2. Extinction spectra as a function of wavelength for Ag and Au NPs deposited on the glass substrates.

J-V characteristics of the compound solar cells with and without NPs were shown in Fig. 3. The NPs density had great influence on the photocurrent of the cells. The best photocurrent enhancements were induced by Ag and Au NPs densities of 12×10^8 and 2×10^8 cm^{-2}, respectively. Consequently, an increase of 13%, and 27% in conversion efficiency following Ag and Au NPs deposition, respectively, were observed (more details were shown in Table 1). Table 1 also showed a reduction in the fill factor (FF) for the cells with NPs. This is result of increase in the surface sheet resistance [8]. Therefore, it indicated that nanoparticle does not stand for p-type contact or by another way almost NPs were in isolation. Fig. 3 also showed that the enhanced short circuit current of the compound solar cell via surface plasmon resonance in Au was higher than that in Ag NPs was. This increase can be result from the lower resonance frequency of Au than that of Ag nanoparticle [11, 15]. Furthermore, Ag NPs are much influenced by oxidation effects that are not present for Au NPs, therefore, in application Ag NPs must be well encapsulated to avoid oxidation. In addition, Ag nanoparticle deposited on a top of cell is high density so they are easy to create multiparticle clusters. As a result, the conversion efficiency is reduced. This is in consequence of the transmitted field amplitude loss by reducing scattering compared to individual particles [16].
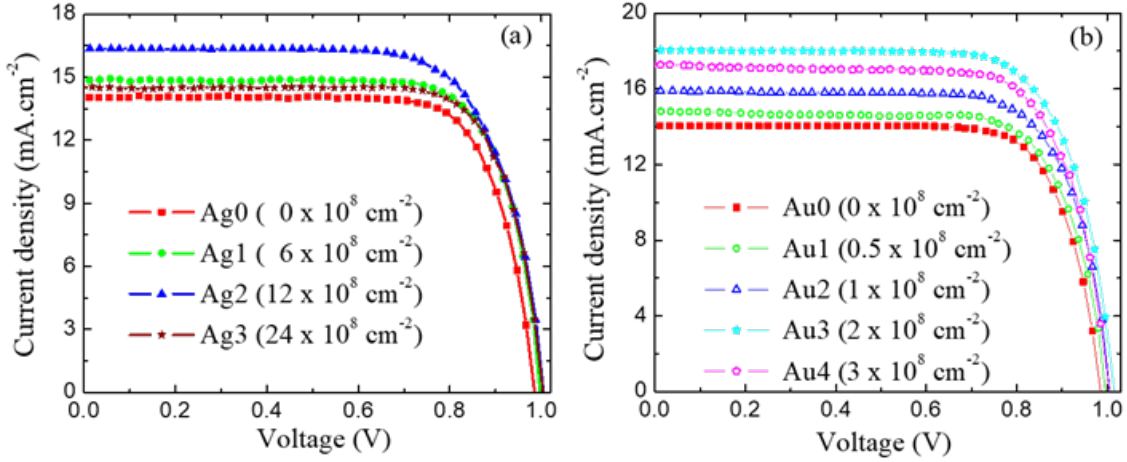
Fig. 3. $J - V$ characteristics of the compound solar cells with and without (a) Ag and (b) Au NPs.

To find out the influence of NPs densities on the short-circuit current or the conversion efficiency, the internal quantum efficiencies (IQE) spectra of the samples with and without Au and Ag NPs were investigated and shown in Fig. 4. The decrease in photocurrent response in the range of photon energy between 2.75 and 3.54 nm was an expected consequence of surface recombination of carriers generated near surface by high-energy photons [17]. The photocurrent response can be improved by utilizing Ag, and Au NPs and strongly depended on their densities. The photocurrent response changes were suitable to the changes of the short circuit current and power conversion efficiency. A broad range above resonance photon energy increase of photocurrent response arises from strong forward scattering of incident photon by NPs. Scattering of incident photon by Ag, and Au NPs yields a reduction in photocurrent response at resonance photon energy, resonance photon energy of Ag, and Au NPs, and below since Ag and Au density up to 12×10^8 and 2×10^8 cm^{-2}, respectively. These reductions were more clearly when Ag and Au density became higher. This was attributed to a phase shift in the scattered wave near the nanoparticle plasmon resonance that results in particle destructive interference between the scattered and the directly transmitted wave [18]. Therefore, the effect of surface plasmon resonance is strongly behavior as high density of NPs in which electric field radiation is higher. At lower density of NPs, the enhanced photocurrent response can be also contributed by photon trapping, surface roughening, and surface plasmon resonance [8,9,19]. This is indicated by the absent of the reduction in photocurrent response below resonance wavelength at low NPs densities. As a result, NPs density plays an important role to improve the conversion efficiency of solar cell.

To compare the influence of Ag and Au NPs on performance of the compound solar cell, the I-V characteristic, IQE, and reflectance spectra of the best photocurrent induced by Ag and Au NPs were shown in Fig. 5 and Fig. 6. It is very clearly to see that, an improvement in photocurrent response by Au is higher than that by Ag NPs, especially in photon energy range from 3.35 eV to 1.70 eV. This could be attributed the broadening of the resonance of Ag nanoparticle that was
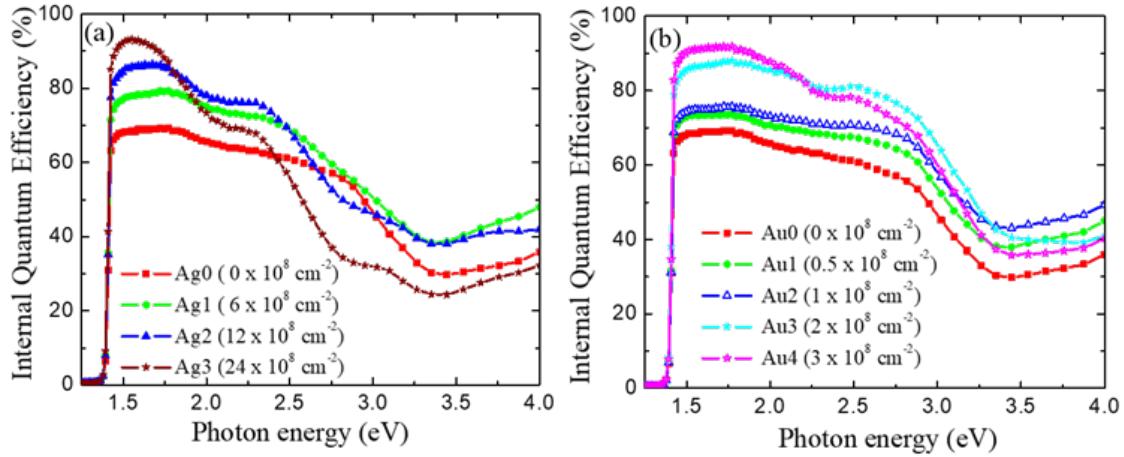
Fig. 4. Internal quantum efficiency (IQE) spectra of the compound solar cells with and without (a) Ag and (b) Au NPs.

shown in the extinction spectra (Fig. 2). Moreover, density of Ag is higher than that of Au NPs therefore Au low density enables the reduction in the loss of incident photon resulting from either absorption or backscattering by the NPs near surface plasmon resonances. In opposition, in the dense Ag NPs case, the plasmonic scattering can be enhanced at photon energy above the surface plasmon resonance that was clearly manifested in Fig. 4(a).
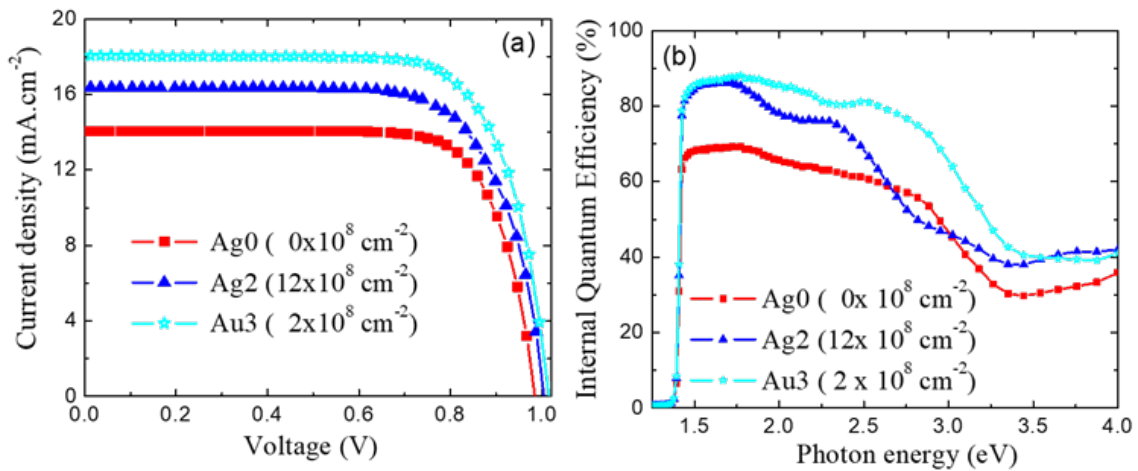

Fig. 5. (a) J – V characteristics and (b) internal quantum efficiency spectra of Ag and Au typical density deposition plotted for comparison.

Figure 6 shows that both of samples with nanoparticle present a reduction of reflection. It indicated that incident photon can be scatted and trapped into p-n junction of cells, increasing the effective path length [9]. The reflection of sample coated by Au NPs is slightly smaller than that of sample coated by Ag NPs. This might relate to density of NPs. Fig. 6 also presents the resonance picks of Au and Ag at 2.25 eV and 2.7 eV, respectively. These picks are small redshifted comparing with the extinction spectra (at 2.3 and 2.82 eV for Au and Ag, respectively) because of Au and Ag deposited on different substrates.
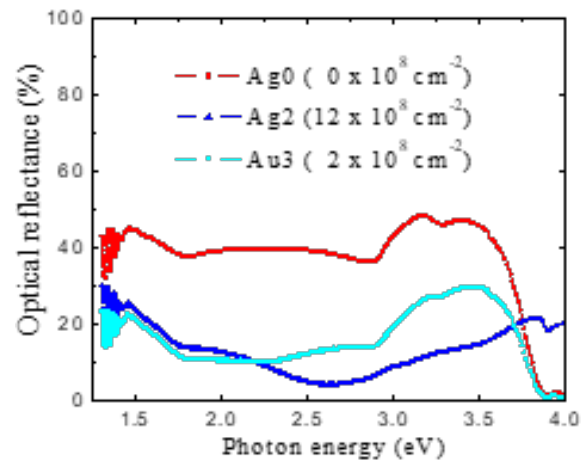

Fig. 6. Reflective spectra of the compound solar cells with and without Ag and Au NPs.

IV. CONCLUSIONS

In conclusion, we have investigated the effects of surface plasmon resonance of gold and silver nanoparticles on the conversion efficiency of a normal design compound solar cells. The conversion efficiency of cells is strongly depended on density and material of nanoparticles. In the dense case can enhance plasmonic scattering at photon energy below resonance but also increase the scattered light destructively at above the resonance photon energy. The loss of incident photon resulting from either absorption or backscattering that behavior in the dense case can be reduced in the sparse case. To improve the power conversion efficiency of the compound solar cells by using surface plasmon resonance in noble metal nanoparticle, Au, due its lower density, lower resonance frequency, and no oxidation effect is thus a better choice than Ag, although it is more expensive. In future work, we suggest that the field enhancement due to an antireflection coating is uniform throughout the semiconductor region after nanoparticles deposition. This is because of the case of the nanoparticles; the field enhancement originates from pockets of high field intensities underneath the particles. Therefore, it might be advantageous for solar cell where such non-uniform field can lead to improved optical absorption and photocurrent generation.

REFERENCES

[1] G. Womack, K. Isbilir, F. Lisco, G. Durand, A. Taylor and J. M. Walls, *The performance and durability of single-layer sol-gel anti-reflection coatings applied to solar module cover glass*, *Surf. Coat. Technol.* **358** (2019) 76.

[2] W. Qarony, M.I. Hossain, A. Salleo, D. Knipp, Y. H. Tsang, *Rough versus planar interfaces: How to maximize the short circuit current of perovskite single and tandem solar cells*, *Mater. Tod. Ener.* **11** (2019) 106.

[3] D. Eisenhauer, C. T. Trinh, D. Amkreutz and C. Becker, *Light management in crystalline silicon thin-film solar cells with imprint-textured glass superstrate*, *Sol. Ener. Mater. Sol. Cell.* **200** (2019) 109928.

[4] S. Morawiec, M. J. Mendes, F. Priolo and I. Crupi, *Plasmonic nanostructures for light trapping in thin-film solar cells*, *Mater. Sci. Semi. Proc.* **92** (2019) 10.

[5] G. Singh and S. S. Verma, *Design and analysis of thin film GaAs solar cells using silver nanoparticle plasmons*, *Phot. Nanostruc. Fund. Appl.* **37** (2019) 100731.

[6] G. Singh, J. S. Sekhon and S. S. Verma, *Enhanced photocurrent in thin-film GaAs solar cells with embedded Al nanoparticles*, *Ener. Sour. Part A: Recov. Util. Env. Eff.* **42** (2020) 815.

[7] W. J. Ho, G. Y. Chen and J. J. Liu, *Enhancing Photovoltaic performance of plasmonic silicon solar cells with ITO nanoparticles dispersed in SiO$_2$ anti-reflective layer*, Mater. **12** (2019) 1614.

[8] K. Nakayama, K. Tanabe and H. A. Atwater, *Plasmonic nanoparticle enhanced light absorption in GaAs solar cells*, *Appl. Phys. Lett.* **93** (2008) 121904.

[9] H. A. Atwater and A. Polman, *Plasmonics for improved photovoltaic devices*, *Nat. Mater.* **9** (2010) 205.

[10] C. F. Bohren and D. R. Huffman, Absorption and Scattering of Light by Small Particles, Wiley-Interscience, New York (1998).

[11] K. R. Catchpole and A. Polman, *Plasmonic solar cells*, *Opt. Exp.* **16** (2008) 21793.

[12] D. Derkacs, W. V. Chen, P. M. Matheu, S. H. Lim, P. K. L. Yu and E. T. Yu, *Nanoparticle-induced light scattering for improved performance of quantum-well solar cells*, *Appl. Phys. Lett.* **93** (2008) 091107.

[13] C. O. McPheeters, C. J. Hill, S. H. Lim, D. Derkacs, D. Z. Ting and E. T. Yu, *Improved performance of In(Ga)As/GaAs quantum dot solar cells via light scattering by nanoparticles*, *J. Appl. Phys.* **106** (2009) 056101.

[14] M. Losurdo, M. M. Giangregorio, G. V. Bianco, A. Sacchetti, P. Capezzuto and G. Bruno, *Enhanced absorption in Au nanoparticles/a-Si:H/c-Si heterojunction solar cells exploiting Au surface plasmon resonance*, *Sol. Ener. Mat. Sol. Cell.* **93** (2009) 1749.

[15] S. Pillai, K. R. Catchpole, T. Trupke and M. A. Green, *Surface plasmon enhanced silicon solar cells*, *J. Appl. Phys.* **101** (2007) 093105.

[16] D. M. Schaadt, B. Feng and E. T. Yu, *Enhanced semiconductor optical absorption via surface plasmon excitation in metal nanoparticles*, *Appl. Phys. Lett.* **86** (2005) 063106.

[17] S. M. Sze, Physics of Semiconductor Devices, Wiley, New York (1981).

[18] S. H. Lim, W. Mar, P. Matheu, D. Derkacs and E. T. Yu, *Photocurrent spectroscopy of optical absorption enhancement in silicon photodiodes via scattering from surface plasmon polaritons in gold nanoparticles*, *J. Appl. Phys.* **101**, (2007) 104309.

[19] T. H. Chang, P. H. Wu, S. H. Chen, C. H. Chan, C. C. Lee, C. C. Chen and Y. K. Su, *Efficiency enhancement in GaAs solar cells using self-assembled microspheres*, *Opt. Exp.* **17** (2009) 6519.