Light Scattering Effects by Silver Nano-Particles on the Surface Protection Sheet of an Amorphous Silicon Solar Cell

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We have numerically investigated the effects of light scattering by silver nano-particles on the surface protection sheet of an amorphous silicon solar cell. The structure consists of two silver nano-particles, a protection sheet, an indium tin oxide layer, and an amorphous silicon solar cell. Two silver nano-particles are put on the protection sheet of the solar cell. The larger diameter of silver nano-particles increases the transmission intensity of the structure at the peak wavelength of 417 nm. The appropriate gap between two silver nano-particles on the protection sheet of the amorphous silicon solar cell increases the transmission intensity of the structure compared with that of the solar cell with less gap at the incident light wavelength of 554 nm. [DOI: 10.1380/ejssnt.2015.83]

Keywords: Plasmon; Nano-particles; Light scattering

I. INTRODUCTION

A lot of researches on an availability of renewable energies are being carried out for solving an environmental problem. A photovoltaic generation which is one of renewable energies is studied by many researchers for increasing the conversion efficiency of a solar cell. To increase the conversion efficiency of a solar cell, light-absorption of a solar cell needs to be increased. In order to increase light-absorption of a solar cell, various methods have been proposed by many research groups [1–10]. Reducing a scattering light on a surface of a solar cell [5] and extending absorption wavelength to infrared [11] are examples of the increase of the light-absorption. To use localized surface plasmon resonances (LSPRs) is one of methods for increasing light-absorption of a solar cell. The method using LSPRs applies an electric field enhancement of LSPRs to increase the light-absorption of the solar cell [3–9]. The electric field enhancement of LSPRs is effective to the increase of the light-absorption of solar cells by putting metal particles such as silver and gold on solar cells directly or very closely. In contrast, solar cells which are covered with surface protection sheets can not apply the structure of directly putting metal particles because surface protection sheets prevent metal particles from being put directly on solar cell materials. We proposed the structure using light scattering by metal nano-particles on surface protection sheets for increasing light-absorption of solar cells covered with surface protection sheets. In order to increase the light-absorption of solar cells, methods of using light scattering by metal nano-particles have been reported [6, 12–14]. However, details of light scattering effects by metal nano-particles on the surface protection sheet have not been reported previously. Optimum size and arrangement of metal nano-particles for increasing light-absorption of solar cells have not been clarified yet.

In this study, we investigated the effects of light scattering by metal nano-particles with different size and arrangement on the transmission intensity of the designed structure. We have adopted silver nano-particle as a metal particle and have adopted amorphous silicon as a solar cell. A silver nano-particle has high scattering efficiency at visible wavelengths and a silver nano-particle with larger diameter brings the increase of forward light scattering [15]. We have applied the finite-difference time-domain (FDTD) method to numerically optimize silver nano-particles. The FDTD simulations are performed by MIT Electromagnetic Equation Propagation (Meep) [16].

II. SIMULATION MODELS

Figure 1(a) shows the over all simulation configuration of silver nano-particles on the surface protection sheet of the amorphous silicon solar cell. Figure 1(b) shows the configuration from top view. The structure consists of the surface protection sheet, the indium tin oxide (ITO) layer, and the solar cell. The height of the surface protection sheet, the ITO layer, and the solar cell are 300, 200, and 400 nm, respectively. The diameter of the silver nano-particle is denoted by $d$ in Fig. 1. The gap between two nano-particles that are put on the surface protection sheet is denoted by $g$ in Fig. 1. The refractive index of the surface protection sheet and ITO are set to 1.45 and 1.80, respectively. The permittivity of the amorphous silicon and silver is implemented with a Drude-Lorentz model [10]. The remaining area is composed of air. The incident light of which polarization is $x$ and $y$ directions irradiated the solar cell in the $x$–$y$ plane from 300 nm above silver nano-particles. The periodic boundary condition are applied in $X$ and $Y$ directions. The perfect matched layer is placed in $Z$ direction. The transmission light was detected at the boundary of the ITO layer and the solar cell. The transmission intensity was found by making comparison between the transmission of the structure with nano-particles and that of the structure without nano-particles.

III. RESULTS AND DISCUSSION

To obtain the optimum values of $d$, we investigate the effect of nano-particles on the transmission with $d$ varied from 160 to 240 nm. $g$ is set to 0 nm. Figure 2 shows transmission intensities of the structure as a function of incident light wavelengths between 400 and 600 nm. $d$ is
FIG. 1. Schematics of silver nano-particles on the surface protection sheet of the amorphous silicon solar cell. (a) the over all simulation configuration and (b) the configuration from top view.

FIG. 2. Transmission intensities of the structure as a function of incident light wavelengths. The solid, broken, and dotted lines correspond to transmission intensities for \( d \) of 160, 200, and 240 nm, respectively. Transmission intensities are set to 0 dB when the transmission light of the structure with silver nano-particles corresponds to that of the structure without silver nano-particles. The maximum transmission intensities of \( d \) of 160, 200, and 240 nm are 0.18, 0.26, and 0.32 dB at the wavelength of near 417 nm, respectively. In comparison with the transmission of the structure without silver nano-particles, that of the structure with silver nano-particles \( d \) increase 4.3, 6.0, and 7.7 % at incident light wavelengths of 417, 416, and 417 nm, respectively. Other local maximum transmission intensities of \( d \) of 160, 200, and 240 nm are 0.08, 0.08, and 0.03 dB at the wavelength of 543, 554, and 557 nm, respectively. Wavelengths of these maximum transmission intensities approximately correspond to the wavelength of LSPRs that are excited on silver nano-particles [17]. The minimum transmission intensities of \( d \) of 160, 200, and 240 nm are \(-0.14, -0.14, \) and \(-0.21 \) dB at incident light wavelengths of 495, 464, and 472 nm, respectively. Wavelengths of local maximum transmission intensities are almost correspond in the diameter of silver nano-particles that ranges from 160 to 240 nm. To investigate detailedly the reason why the transmission intensity increases at the incident light wavelength of near 417 nm, we have compared the electric field intensity profiles of the solar cell with \( d \) of 200 and \( g \) of 0 nm at incident light wavelengths of 416 and 414 nm. Figure 3 shows electric field intensity profiles at the center of silver nano-particles in incident light wavelengths of (a) 416 and (b) 464 nm. The diameter of silver nano-particles [denoted by \( d \) in Fig. 1(b)] is set to 200 nm. The gap between two silver nano-particles [denoted by \( g \) in Fig. 1(b)] is set to 0 nm.

FIG. 3. Electric field intensity profiles at the center of silver nano-particles in incident light wavelengths of (a) 416 and (b) 464 nm. The diameter of silver nano-particles [denoted by \( d \) in Fig. 1(b)] is set to 200 nm. The gap between two silver nano-particles [denoted by \( g \) in Fig. 1(b)] is set to 0 nm.
wavelengths between 400 and 600 nm. $d$ is set to 200 nm. In Fig. 4, the solid, broken, and dotted lines indicate transmission intensities for $g$ of 0, 80, and 160 nm, respectively. The maximum transmission intensities of $g = 0, 80$, and 160 nm are 0.26, 0.28, and 0.27 dB at the wavelength of near 417 nm, respectively. In the case of the incident light wavelength of 417 nm decreases, we compared electric field intensity profiles of $g = 0$ nm with that of $g = 160$ nm. Figure 5 shows the electric field intensity profiles at just under silver nano-particles for (a) $g = 0$ nm and (b) $g = 160$ nm. $d$ is set to 200 nm and the wavelength of the incident light is 554 nm. Electric field intensity of the structure with $g = 0$ nm is large only between silver nano-particles because LSPRs of two nano-particles interact [18–20]. By contrast, electric field intensity with $g = 160$ nm is large around both silver nano-particles because LSPRs are excited on each silver nano-particle. In the case of $g = 160$ nm, light scattered by silver nano-particles is larger compared to the case of $g = 0$ nm. Thus, the transmission intensity of the structure with $g = 160$ nm increases compared with that of $g = 0$ nm. The $g$ needs an appropriate gap for increasing light scattering by silver nano-particles on the surface protection sheet.

![FIG. 4. Transmission intensities of the structure with two silver nano-particles as a function of incident light wavelengths. The solid, broken, and dotted lines correspond to transmission intensities for $g$ of 0, 80, and 160 nm, respectively. $d$ is set to 200 nm.](image-url)

![FIG. 5. Electric field intensity profiles at just under silver nano-particles for (a) $g = 0$ nm and (b) $g = 160$ nm. $d$ is set to 200 nm and the wavelength of the incident light is 554 nm.](image-url)

IV. CONCLUSION

We have numerically investigated the effects of light scattering by silver nano-particles on the surface protection sheet of an amorphous silicon solar cell. The transmission intensity of the structure with the larger diameter of $d$ is increased at the peak wavelength of 417 nm. Peak wavelengths of the transmission intensities of the structure with silver nano-particles of $d = 160, 200$, and 240 nm and $g = 0$ nm are wavelengths of near 417 nm, respectively. The transmission intensity of the structure with silver nano-particles of $d = 240$ nm and $g = 0$ nm increases 7.7 % compared with the structure without silver nano-particles at the incident light wavelength of 417 nm. The transmission intensity of the structure with silver nano-particles of $d = 200$ nm increases 26.6 % with $g$ being varied from 0 to 160 nm at the incident light wavelength of 554 nm. An appropriate gap between silver nano-particles reduces the interaction of silver nano-particles. Then the LSPRs is excited on each silver nano-particle. Therefore, the appropriate gap of $g = 160$ nm enables the structure to increase the transmission intensity. In contrast, the small gap of $g = 0$ nm causes the interaction between silver nano-particles.

This study clarifies light scattering by silver nano-particles on the surface protection sheet of an amorphous silicon solar cell. Results of this study enable to increase the efficiency of solar cells in the future.

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