Analytical study of enhanced optical absorption of nanoscaled light-trapping objects by silver nanoparticles

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The effective mode volume model is employed to study an enhanced light absorption of various nanoscaled objects which are composition of absorption layers in solar cells when they are positioned in close proximity to Ag nanospheres. Furthermore, a procedure for optimal design of Ag nanoparticles for a promising improvement of light absorption of nanoscaled objects is presented. 2010 Optical Society of America

1. Introduction

Thin-film solar cells are promising candidates for high efficiency and cost effectiveness of photovoltaic devices. In particular, microcrystalline silicon ($\mu\text{c-Si:H}$) and InGaN-based solar cells have attracted numerous attention in recent years [1]. One of the foremost challenges in designing those thin-film solar cells is to design an efficient light-trapping of absorption layers. For enhancing the absorption efficiency, we normally prefer to employ a thin i-layer or absorption layer for enhancing the build-in field such that it can effectively separate electrons and holes generated. However, with the reduced i-layer thickness sunlight absorption may become ineffective leading to the decrease of the energy conversion efficiency of a solar cell. To overcome this problem one of the most commonly used method is the utility of metallic nanoparticles (NPs) embedded in the absorption layer to generate localized surface plasmon (LSP). An LSP mode can effectively absorb light around the resonance frequency.

In this work we investigate the influence of silver (Ag) NPs on light absorption of various nanoscaled objects which are composition of absorption layers in thin-film solar cells using the effective mode volume theory. We show that an enhanced light absorption of those objects is obtained when they are positioned in close proximity to Ag nanospheres while an enhancement factor is strongly dependent on sphere size, absorption cross section and separation between the object and Ag sphere. Furthermore, based on the analytical results of the enhancement factor we present a procedure for optimal design of Ag NPs for a promising improvement of light absorption of nanoscaled objects.

2. Analytical model of enhancement of optical absorption

The analytical model used to predict an enhancement of light absorption in this work is the effective mode volume theory presented in [2]. When an incident light beam focuses to a nanosphere, it can be coupled into the dipole mode (the smallest-order mode). This excited dipole mode has a resonant frequency and an effective mode volume. The optical absorption can be described as a two-step process. First, the energy from free-space modes contained in the focused beam gets coupled into the dipole mode with an in-coupling coefficient. The second step is that the energy in the dipole mode actually gets absorbed by molecules with an absorption

cross section (σ_a) located at distance d away from the metal sphere. This results in an enhanced light absorption of molecules. The absorption enhancement factor (F_a) is defined as the ratio of the absorption rate of dipole energy to that of the incident wave at the focusing spot in the absence of the metal sphere.

For an optimal design of metallic NPs the procedure can also be split into two steps. First, with a given total absorption cross section $N_a\sigma_a$ and NP size the enhancement factor F_a is found at a certain resonance frequency. The second step is to increase the NP size with fixed $N_a\sigma_a$ to calculate F_a . From the enhancement factor spectrum the optimal NP size can be found.

3. Results

We study the influence of Ag NPs on the light absorption of intrinsic InGaN and Si molecules. Figure 1 shows the absorption enhancement as a function of sphere radius a wherein the absorbing molecules with a range of total absorption cross section are placed at $d=5$ nm from the Ag NP. For Ag/InGaN the optimal radius of Ag NP is found at 41 nm with a resonance frequency 603.5 nm in combination with 100 nm^2 total absorption cross section while with $N_a\sigma_a = 300 \text{ nm}^2$ the optimal radius is found at 50 nm with a resonance frequency 604 nm. The same figure shows that for Ag/Si the optimal radius of Ag NP is found at 51 nm with a resonance frequency 730 nm in combination with $N_a\sigma_a = 100 \text{ nm}^2$ while $N_a\sigma_a = 300 \text{ nm}^2$ the optimal radius is found at 63 nm with the same resonance frequency. From the figure it is seen that the enhancement factor is strongly dependent on the NP size and total absorption cross section. Indeed, the stronger the original absorption the less enhancement is attainable.

The enhanced light absorption as a function of Ag sphere radius a with respect to the separation d between the molecule (a total absorption cross section is fixed at 300 nm^2) and the NP is depicted in Fig. 2. The dependent enhancement factor on a distance d is clearly seen in the figure. Unsurprisingly, the larger the distance d the smaller the optimal radius a is observable.

Fig. 1. Absorption enhancement as a function of sphere radius a with respect to a range of total absorption cross section.

Fig. 2. Absorption enhancement as a function of sphere radius a with respect to a range of separation between molecule and Ag sphere.

References

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