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RESEARCH ARTICLE

Plasmonic light trapping for wavelength-scale silicon solar absorbers

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Abstract Light trapping is of critical importance for constructing high efficiency solar cells. In this paper, we first reviewed the progress we made on the plasmonic light trapping on Si wafer solar cells, including Al nanoparticle (NP)/SiN_x hybrid plasmonic antireflection and the Ag NP light trapping for the long-wavelength light in ultrathin Si wafer solar cells. Then we numerically explored the maximum light absorption enhancement by a square array of Ag NPs located at the rear side of ultrathin solar cells with wavelength-scale Si thickness. Huge absorption enhancement is achieved at particular long wavelengths due to the excitation of the plasmon-coupled guided resonances. The photocurrent generated in 100 nm thick Si layers is 6.8 mA/cm^2, representing an enhancement up to 92% when compared with that (3.55 mA/cm^2) of the solar cells without the Ag NPs. This study provides the insights of plasmonic light trapping for ultrathin solar cells with wavelength-scale Si thickness.

Keywords solar cells, light trapping, plasmonic, ultrathin Si, wavelength-scale

1 Introduction

Recently, nano-scale light trapping strategies, such as plasmonic nanoparticles (NPs) [1–19], dielectric nanospheres [20,21] and high-index nanostructures [22–26] have been extensively explored to enhance the light absorption in the solar cells due to their unique optical properties. Among these strategies, plasmonic NPs have shown impressive absorption enhancement by employing the strong far-field scattering and/or near-field light concentration induced by the surface plasmon resonances of metallic NPs [1,2]. The plasmonic resonances of the NPs can be easily tuned by the material, shape, size and surrounding medium, providing highly flexible designs. Although plasmonic light trapping was originally proposed to solve the light absorption issues associated with thin film solar cells, it can potentially address the light absorption issues related with the Si wafer solar cells, which are the dominant product on the photovoltaic market at least in two aspects.

Conventionally, pyramid textured surface with a feature size up to ten microns has been demonstrated highly effective as a light trapping strategy in the single crystalline Si (sc-Si) wafer solar cells. However, this structure cannot be formed on multicrystalline Si (mc-Si) wafers by chemical etching due to the different crystal orientation of the Si surface. This leads to an ineffective textured surface with relatively weak light trapping capabilities and thus lower energy conversion efficiency. Plasmonic NPs can potentially compensate this by the preferentially forward scattering [4,5]. The other aspect that plasmonic NPs can play a significant role is the light losses of the weakly-absorbed long-wavelength light in ultrathin Si wafer cells. Driven by the cost reduction, ultrathin Si solar cells have attracted a great deal of interests due to their better electrical performance and significant reduction in Si usage [25–29]. However, the pyramid textured surface is not applicable to ultrathin Si wafers with a few microns due to geometry limitation. In this case, the plasmonic NPs provide a nano-scale light trapping strategy intrinsically applicable to ultrathin Si wafers with a few microns [3].

In this paper, we first reviewed the recent progress we made on plasmonic light trapping on Si wafer solar cells, including the Al NP/SiN_x hybrid plasmonic antireflection and the Ag NP light trapping on the ultrathin Si wafers with the Si thickness ranging from 180 to 1 μm [3–6]. Then we numerically explored the maximum potential of the

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plasmonic Ag NP light trapping on the ultrathin Si wafers with wavelength-scale Si thickness. In this thickness range, the wave effect is dominant and the conventional light trapping limit could be potentially broken down [30].

2 Al nanoparticle/SiN$_x$ hybrid plasmonic antireflection

Integrating the plasmonic NPs on the front side of the Si wafer solar cells reduces the light reflection and improves the light incoupling of the incident light into the underlying Si layers. The noble metal NPs, including Ag and Au, have been investigated on the front surface, demonstrating minor absorption enhancement and even worse effect on the solar cells [17,18]. This is mainly due to the reduced light incoupling at the short wavelengths below the surface plasmon resonances caused by the Fano effect, i.e., the destructive interference between the incident light and the scattered light. We have demonstrated that the low cost and earth-abundant Al NPs can overcome this issue and achieve a broadband light absorption enhancement by blue shifting the resonance wavelength away from the important solar spectrum [4,5]. The maximum light incoupling enhancement by the Al NPs predicted by the finite difference time domain (FDTD) simulation is 28.7%, which is much larger than that induced by Ag or Au NPs. Once combined with the SiN$_x$ anti-reflection coating, Al NPs can produce a 42.5% enhancement, which is 4.3% higher than the standard SiN$_x$. Experimentally, we also verified this broadband light incoupling and demonstrated a photocurrent increase of 0.4 mA/cm^2 for the commercial mc-Si solar cells, with the energy conversion efficiency increased from 14.2% to 14.5%. After optimization of the NP integration, the photocurrent can potentially be increased by 1 mA/cm^2.

3 Ag nanoparticle light trapping on ultrathin Si wafers

As the thickness of the Si wafers reduces, the light losses at the long wavelengths become severe. Integrating the plasmonic NPs at the rear side of the solar cells enables a highly efficient light absorption in this range without influence on the short-wavelength light. When the light enters the Si layer and travels to the bottom side of the solar cells, strong scattering occurs due to the plasmonic resonances, leading to an angular distribution of the reflected light. As a result, the light can be trapped inside the Si layers by the total internal reflection, which increases the light path length. We have demonstrated a huge absorption enhancement in the Si wafers with the Si thickness ranging from 180 to 1 μm [3,6]. For planar solar cells with 180 μm thick Si, the absorption enhancement was observed at wavelengths above 900 nm, leading to a photocurrent increase of 0.3 mA/cm^2 [6]. The thinner the Si wafer is, the larger the absorption enhancement is. For a highly passivated Si surface, the open circuit voltage of the solar cells increases as the Si thickness reduces. We predicted that, using a properly designed NP architecture, 20 μm thick Si wafer solar cells are equally efficient as the 180 μm thick Si solar cells by combining the absorption enhancement with the benefit of thinner wafer induced open circuit voltage increase. This represents a 90% material saving without any efficiency loss, providing a viable solution for dramatically increased cost-effectiveness for Si wafer solar cells [3].

4 Ultrathin Si absorbers with wavelength-scale thickness

In this section, we extend the Ag NP light trapping to the ultrathin Si wafer solar cells with wavelength-scale Si thickness. Figure 1 schematically illustrates the plasmonic solar cell geometry we studied. The solar cells consist of SiN$_x$/Si layer/Ag NP embedded SiO$_2$/Ag reflector. An optimized 75 nm thick SiN$_x$ layer is positioned on the front surface of the Si layer to reduce the light reflection while the Ag reflector is employed at the back side to reflect the light transmitted out of the Si layer. Hemispherical plasmonic Ag NPs are embedded in the dielectric layer SiO$_2$ between the Si layer and the Ag reflector.

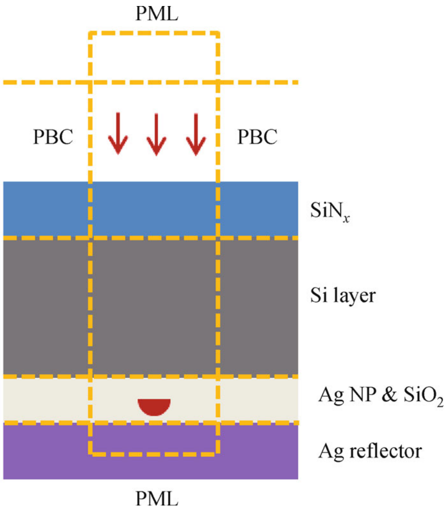

Fig. 1 Schematic diagram of the plasmonic solar cell structure and the simulation geometry. PML: perfectly matched layer; PBC: periodic boundary condition

4.1 Numerical modeling

FDTD simulation method [31] was used to investigate the light absorption in each layer of the solar cells, with the simulation geometry shown in Fig. 1. A plane wave source (red arrow) ranging from 300 to 1200 nm was employed to illuminate the solar cells. The vertical boundaries used in the simulation are perfectly matched layers (PMLs) while the lateral boundaries are periodic boundary conditions (PBCs). This simulates a square array of Ag NPs without the influence of the reflected light from the vertical boundaries. Four transmission monitors (dash lines) are employed to obtain the reflection of the solar cells and the absorption in the layers of Si, Ag NP embedded SiO_2 and Ag reflector. The refractive index data of Ag NPs were obtained from Palik [32] and that of the Si from Green [33]. A non-absorbing SiN_x layer was used with the real part of its refractive index measured from a commercial solar cell. The particle diameter, *D*, and the space between the NPs, *S*, were investigated for different Si thicknesses. The space between the Si and the Ag NPs is set as 20 nm while that between the Ag NPs and the Ag reflector is kept at 50 nm. The thickness of the Si layer was chosen as 50, 100, 200, 500 nm and 1 μm, respectively. The photocurrent was obtained by integrating the Si absorption with the standard air mass 1.5 global solar photon fluxes.

4.2 Results and discussion

Figure 2 shows the optimization map of the photocurrent generated in 100 nm thick Si layers. The optimized photocurrent is 6.8 mA/cm^2 when the NP diameter *D* and the space *S* are both 250 nm. This represents an enhancement of 92% when compared with that (3.55 mA/cm^2) of the solar cells without Ag NPs integrated. Interestingly, the enhancement occurs among the entire optimization range. This offers high flexibility for the practical Ag NP integration. The optimization of the parameters is a trade-off between a few factors. For the particle size, when the diameter is below 100 nm, the scattering spectra of the particles are quite narrow while increasing the particle size to above 200 nm would lead to higher order plasmon excitation, reducing the coupling efficiency of the scattered light into Si. For the space between the NPs, when it is too small, the absorption loss in the particles is relatively large. In contrast, large space could not ensure a full area light-material interaction.

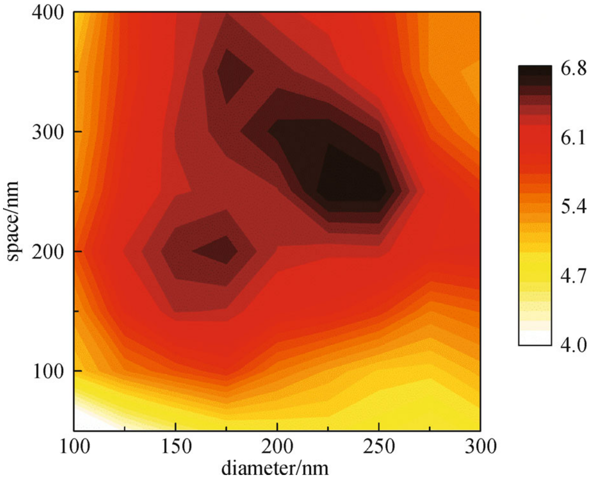

Fig. 2 Optimization map of the photocurrent as a function of the NP diameter and the space between the NPs

The spectra of the solar cells with the optimized Ag NPs are shown in Fig. 3, in comparison with that without NPs. As seen in Fig. 3(a), the absorption in the Si layer is dramatically increased for the wavelength from 500 to 1200 nm, with some distinct peaks appeared, particularly at the wavelength of 634 nm, which approximately matches the solar peak intensity. These peaks are the guided resonances in the Si layer of the solar cells, excited by the coupling of the scattered light from the Ag NPs. At the same time, the two peaks within the short wavelength range 300 – 500 nm are the Fabry-Perot resonances in the Si layer. With the NP integrated, these two peaks show minor blue shifts. The light losses in the SiO_2 layer with the NPs embedded and the Ag reflector are also enhanced, as shown in Figs. 3(b) and 3(c). Due to the Ag NP scattering, the guided resonances are also excited in the SiO_2 layer, leading to multiple interactions between the light and Ag NPs. This dramatically increases the absorption cross-section of the Ag NPs, leading to a significant absorption loss. The enhanced loss in the Ag reflector is due to the energy leaking of the guided resonance in the SiO_2 layer. The huge absorption enhancement in these three layers leads to a corresponding reflection reduction, as shown in Fig. 3(d).

To understand these optical behaviors, we simulate the electrical field distributions in the solar cells with and without Ag NPs. Figures 4(a) and 4(b) present the field distribution of the cross-section for the solar cell without Ag NPs at the wavelength of 400 and 800 nm, corresponding to the frequencies on and off the Fabry-Perot resonance. Clearly, the Fabry-Perot interference pattern is observed at 400 nm with larger electric field magnitude than that at 800 nm. Figures 4(c) and 4(d) give the field for the solar cells with Ag NPs at 394 and 634 nm. The field pattern at 394 nm is still dominant by the Fabry-Perot resonance whereas the field for the 634 nm is essentially a guided mode pattern. The presence of the Ag NPs also supports some gap modes, as demonstrated by the field pattern in the space between the NP and the Si layer. The localized energy around the surface of the Ag NP, particularly at the sharp corners would eventually convert to heat due to the ohmic damping. The other distinct peaks at the long wavelengths above 500 nm in Fig. 3(a) have similar field distributions with that at 634 nm.

This light trapping strategy applies to a wide range of Si thicknesses. Figure 5 shows the optimized photocurrent as a function of the Si thickness. As seen in the figure, the current dramatically reduces from 14.6 to 2 mA/cm^2 when the Si thickness decreases from 1 μm to 50 nm. Due to the presence of the Ag NPs, the current are significantly increased at each thickness, with the largest enhancement (93%) for the 50 nm thickness.

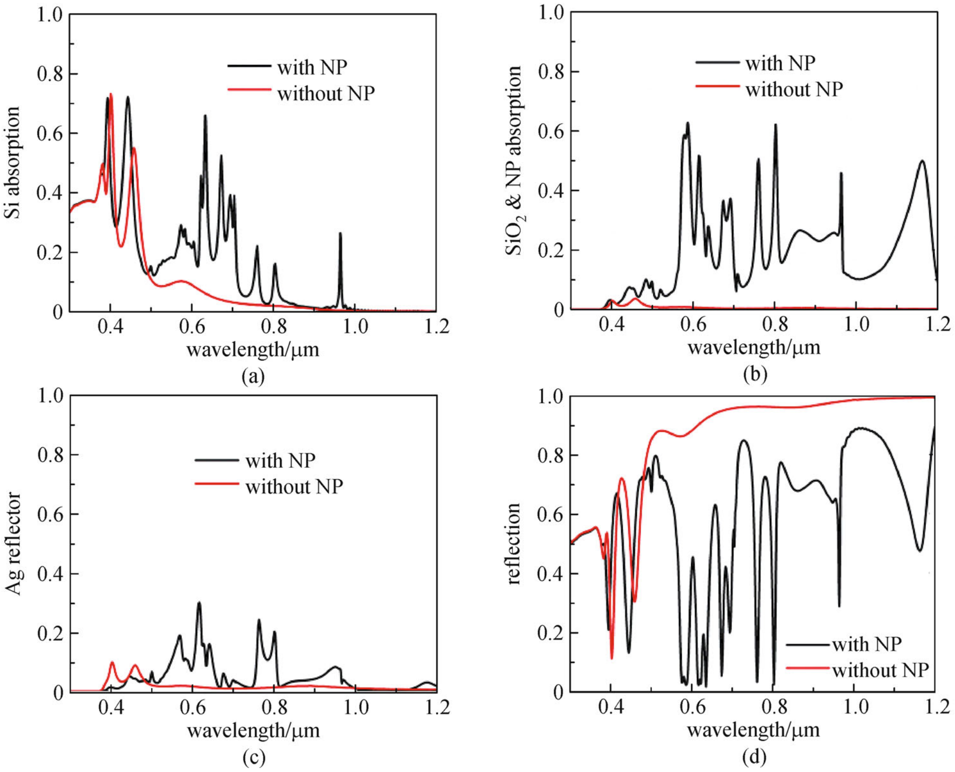

Fig. 3 Spectra of the absorption in the (a) Si layer, (b) SiO_2 layer with Ag NPs, (c) Ag reflector and (d) the reflection for the solar cells integrated with the optimized Ag NPs, referenced with the solar cells without Ag NPs

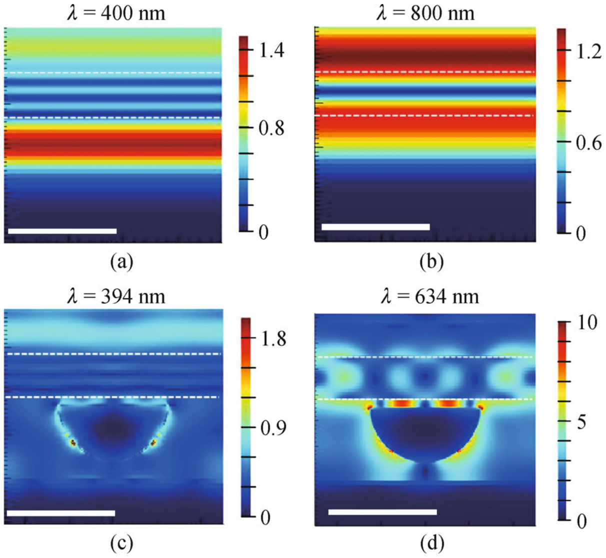

Fig. 4 Electrical field distributions for the solar cells without Ag NPs at the wavelengths of (a) 400 nm and (b) 800 nm and those for the solar cells with the optimized Ag NPs at the wavelengths of (c) 394 nm and (d) 634 nm. The Si layers are highlighted by the white dash lines (Scale bar: 250 nm)

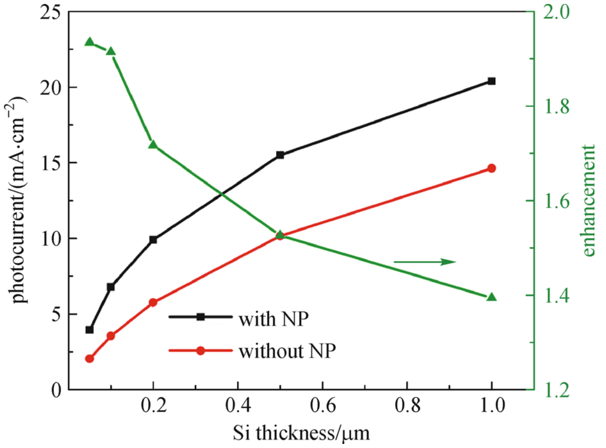

Fig. 5 Optimized photocurrent density as a function of the Si thickness for the solar cells with and without Ag NP integration. The photocurrent enhancement is shown for reference

5 Conclusions

In conclusion, we have reviewed the progress we made on plasmonic light trapping on Si wafer solar cells and demonstrated significant absorption enhancement for ultrathin Si solar cells with wavelength-scale Si thickness by using the rear side located plasmonic Ag NPs. An enhancement up to 92% for 100 nm thick Si layers is predicted by the numerical simulation. Distinct guided resonance peaks are observed in the absorption spectra, contributing to this large absorption enhancement.

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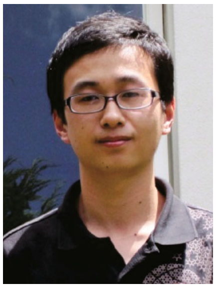

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