Towards ultra-thin plasmonic silicon wafer solar cells with minimized efficiency loss

Yinan Zhang¹, Nicholas Stokes¹, Baohua Jia¹, Shanhui Fan² & Min Gu¹

¹Centre for Micro-Photonics, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia, ²Department of Electrical Engineering, Ginzton Laboratory, Stanford University, Stanford, California 94305, United States.

The cost-effectiveness of market-dominating silicon wafer solar cells plays a key role in determining the competitiveness of solar energy with other exhaustible energy sources. Reducing the silicon wafer thickness at a minimized efficiency loss represents a mainstream trend in increasing the cost-effectiveness of wafer-based solar cells. In this paper we demonstrate that, using the advanced light trapping strategy with a properly designed nanoparticle architecture, the wafer thickness can be dramatically reduced to only around 1/10 of the current thickness (180 μm) without any solar cell efficiency loss at 18.2%. Nanoparticle integrated ultra-thin solar cells with only 3% of the current wafer thickness can potentially achieve 15.3% efficiency combining the absorption enhancement with the benefit of thinner wafer induced open circuit voltage increase. This represents a 97% material saving with only 15% relative efficiency loss. These results demonstrate the feasibility and prospect of achieving high-efficiency ultra-thin silicon wafer cells with plasmonic light trapping.

Being the dominant products on the photovoltaic market, crystalline Si wafer solar cells have been the intensive research focus for years. Increasing the energy conversion efficiency and reducing the cost have been the two major driving forces for the solar industry and academic research to make solar electricity more competitive with the conventional fossil fuel. An effective way of cost reduction is to make the wafer thinner since the wafer cost accounts for approximate 50% of the solar cell cost. In the past few decades, the wafer thickness has been reduced from 400 μm to the current 180 μm and the trend of reduction is continuing. Apart from the cost saving consideration, thinner wafer can potentially lead to a higher open circuit voltage, Voc, due to the lower bulk recombination and more efficient electron-hole pair extraction.

However, the wafer thickness reduction poses a great challenge for efficiency maintenance due to the significant light absorption decline at the longer wavelengths, especially when the wafer thickness is reduced to below 50 μm. The longer wavelength light has a lower absorption coefficient, requiring a larger travelling distance in Si to be completely absorbed. To fully appreciate the benefits of wafer-thickness-reduction-induced cost savings and higher electrical performance, advanced light trapping technology targeting the longer wavelength region of the solar spectrum is pressingly required to be developed.

Metallic nanoparticles, which support localized surface plasmons, have been demonstrated to be able to provide advanced light trapping mechanisms to significantly enhance the light absorption in solar cells by the scattering and near-field effects. So far, most of the plasmonic solar cell research has been focused on the thin film technology. Only limited work has been conducted on Si wafer solar cells using Ag or Al nanoparticles due to the fact that thick silicon wafer cells absorb almost 90% of the sun light higher than the bandgap. There is limited room to further increase. However, as the wafer thickness reduces, the nanoparticles are expected to play an increasingly important role.

In this manuscript, through theoretically exploring the maximum potential of the light absorption that can be achieved by metallic nanoparticle arrays within the Si wafer solar cells, we find that plasmonics light trapping plays a pivotal role in the efficiency enhancement of ultra-thin wafer cells of thickness down to 1 μm. We further identify that the critical design parameters of the ordered nanoparticle array for maximum light absorption enhancement are wafer-thickness dependent. Furthermore, we experimentally verify the large absorption enhancement within ultra-thin Si wafers by plasmonic nanoparticles. The insights in this article open up a new perspective and guidance for achieving high efficiency wafer solar cells at the ultra-thin Si thickness.
Fig. 1a shows the thick 180 μm solar cell with a standard configuration (cell without nanoparticles) used throughout this study, consisting of a 75 nm SiNx antireflection coating (ARC) layer on the surface of a Si wafer. 75 nm is the optimized thickness for SiNx as an ARC layer. An optically thick Al back reflector is located underneath the wafer. Figs. 1b and 1c identify, respectively, the ultra-thin solar cells with the light trapping nanoparticles located on the front surface of the SiNx ARC and embedded in a SiO2 dielectric layer positioned between the Si wafer and the Al back reflector. The front nanoparticles can both reduce the light reflection at the front surface due to the optical impedance matching and the light path length increase particularly for the longer wavelengths as a result of the scattering induced angular redistribution of the incident light. The rear nanoparticles also can enhance the light path lengths by scattering. In addition, the scattered light with angles larger than the critical angle of the front interfaces can be trapped inside the Si due to total internal reflection. To avoid the transmittance reduction introduced by the surface plasmon polariton at the longer wavelengths, spherical nanoparticles are used on the front surface to minimize the contact area between the metallic nanoparticles and the substrate, while hemispherical nanoparticles are used on the rear side of the cells due to a better coupling of the scattered light into the Si layer. The SiO2 spacing layer between the Si and Ag nanoparticles is 20 nm, which is a balance between light incoupling and rear surface passivation. Another 100 nm SiO2 layer is designed under the nanoparticles, for electrical isolation.

Fig. 2 shows the optical simulated results of the solar cells. The finite difference time domain (FDTD) method (FDTD Solutions,
Lumerical) was used to investigate the light absorption in the Si layer of the three cell designs in Fig. 1 at the wafer thicknesses of 180, 100, 50, 20, 10, 5, 2 and 1 μm. Perfectly matched layers were used in the vertical direction to avoid the interference of the light reflected from the simulation boundaries and periodic boundary conditions were used in the lateral direction to simulate an ordered array of nanoparticles. A plane wave source ranging from 300 nm to 1200 nm was employed. Refractive index data for metallic nanoparticles were obtained from Palik29, crystalline Si from Green30 and SiNx data was measured from a commercial solar cell. Transmission monitors were employed on the front and rear surfaces of the Si layer to obtain the light transmission into and out of the Si layer thereby the light absorption. The integrated light absorption was calculated by integrating the light absorption over the spectrum and weighting to the AM1.5 standard solar photon spectrum in the 300–1200 nm spectral range. The particle diameter, D, and the coverage, C, were investigated for each design at different wafer thicknesses.

Two metals, Al and Ag, were selected as the front located nanoparticle materials for light trapping while Ag nanoparticles for rear light trapping. Al nanoparticles, with their surface plasmon resonances located in the UV region below the usable solar spectrum edge at 300 nm, have been demonstrated to be able to avoid the light incoupling loss and introduce an extra enhancement in the shorter wavelength range23,27. Ag nanoparticles, however, have larger scattering strength and less particle absorption than the Al nanoparticles at the longer wavelengths. Therefore it is expected that the optimized material for the front located nanoparticles might switch from Al to Ag when the wafer thickness reduces to a certain extent where the light trapping for the longer wavelengths is predominant. While Ag is the best material for the rear side since the only consideration is the longer wavelength light trapping.

Fig. 2a shows the integrated light absorption of the optimized plasmonic nanoparticle enhanced solar cells for different wafer thicknesses, referenced to the standard cell structure, with the detailed data in Supplementary Information. The reduction in the wafer thickness of the standard cells leads to a dramatic absorption decline from around 80% (180 μm) to 33% (1 μm). By using plasmonic nanoparticles either on the front or the rear side of the wafer cells, the light absorption is largely enhanced, with more significant enhancement from the rear located Ag nanoparticles at each wafer thickness. We observe that the integration of rear located Ag nanoparticles allows the wafer thickness to be significantly reduced to 50 μm without a compromise in the light absorption compared to that of the 180 μm standard cell, as indicated in the dashed lines in Fig. 2a. This is further confirmed by the absorption spectrum of the 50 μm wafer cells with rear Ag nanoparticles and the 180 μm standard cells, shown in Fig. 2b. The additional nanoparticle-induced light trapping mechanism completely compensates for the light absorption decline in the wavelengths longer than 800 nm caused by the wafer thickness reduction from 180 μm to 50 μm.

Fig. 2c shows the enhancement of the integrated absorption as a function of the wafer thickness for the optimized particles, relative to the standard cells. For front nanoparticles, it is found that Al is preferred when the Si thickness is above 5 μm with a stable enhancement of approximately 2% whereas Ag outperforms Al for wafer thicknesses of 2 and 1 μm, with enhancements up to 4.7% and 8.6%, respectively. As expected, we observe that the optimized material switches from Al to Ag when the wafer thickness reduces to below 5 μm where longer wavelength light trapping plays a key role in the absorption enhancement. Compared with the front surface nanoparticles, the enhancement of the rear nanoparticles increases from 5.2% to 24.4% when the thickness of Si wafer reduces from 180 μm to 1 μm. We show in Fig. 2d that the absorption spectrum of the 180 μm wafer cell with a standard structure, front integrated Al nanoparticles and rear integrated Ag nanoparticles, individually. Front Al nanoparticles lead to enhancements at both the wavelengths shorter than 500 nm and wavelengths longer than 700 nm with a slight reduction at the middle wavelengths. Whereas for rear Ag nanoparticles, the light absorption at wavelengths longer than 900 nm has been enhanced without any reduction on the shorter wavelengths. This explains the larger enhancement by the rear Ag nanoparticles. Furthermore, the rear nanoparticles have a larger light incoupling efficiency than the front nanoparticles due to the presence of the Al back reflector, which can prevent the light outcoupling to the air through the rear surface.

It is noted that the optimized nanoparticle configuration (particle diameter D and particle coverage C) depends on the wafer thickness with different unabsorbed solar spectrum profiles for light trapping and the Si absorbing capabilities at different wavelengths. The optimization of the particle size is a trade-off between a few factors, including particle absorption and scattering, particle-particle intercoupling, particle-substrate incoupling et al. Small particles exhibit strong absorption and low scattering while large particles shows strong scattering and even higher order scattering modes with a comparatively small particle absorption. Increasing the size of the nanoparticles would reduce the incoupling efficiency due to the increased average distance to the substrate and redshift and broaden the plasmon resonance31. The particle coverage is determined by the scattering cross-sections of the particles and the location of the particles. A particle array with particle separation on the order of wavelength might introduce the intermediate-field hybridized modes, which would change the behavior of light scattering32.

It is interesting to note the optimized diameters of the front Al and Ag nanoparticles increase to relatively large (D > 200 nm) for thin wafers with thicknesses of 1 and 2 μm compared to the nanoparticle diameters for wafers thicker than 5 μm (see Supplementary Information). This is due to the broadband scattering cross-sections of large nanoparticles, which are beneficial for the longer wavelength light trapping. Fig. 3a shows the normalized scattering cross-sections of
the optimized front located Al nanoparticles ($D = 120$ nm and $220$ nm) and Ag nanoparticles ($D = 100$ nm and $240$ nm) for $180$ µm and $1$ µm wafer cells. Clearly, the scattering cross-sections for $220$ nm Al and $240$ nm Ag nanoparticles are extended to the longer wavelengths compared to the narrowband scattering cross-sections for $120$ nm Al and $100$ nm Ag nanoparticles staying below $500$ nm. The optimized $C$ for front Al and Ag nanoparticles remained low at $10\%$ and $5\%$, respectively for different wafer thicknesses above $5$ µm and at $10\%$ for $1$ and $2$ µm wafers, which leads to the ignorable additional cost for the final solar cells.

The optimized diameter $D$ for rear Ag nanoparticles reduces from $240$ nm to $160$ nm (see Supplementary Information) when the thickness of Si wafer decreases, with the scattering cross-sections blue shifting to the shorter wavelengths (Fig. 3b) to match the broadened unabsorbed solar spectrum. The particle coverage $C$ is found to be stabilized at $20\%$. The reason can be explained by the value of the normalized scattering cross-section. It is shown that the scattering cross-sections of the nanoparticles are approximately five times of the geometrical cross-sections, which means $C = 20\%$ is sufficient to fully cover the entire solar cell surface and interact adequately with the incident light.

To verify the significant absorption enhancement by the rear Ag nanoparticles, predicted by the simulation, we experimentally incorporate the Ag nanoparticles on the rear side of ultra-thin Si wafers from $50$ µm to $2$ µm and measured the optical responses by a UV-VIS-NIR spectrometer (Lambda 1050, Perkin Elmer) in the $300–1200$ nm spectral range with an integrating sphere set up, which is used for collecting the scattered light. The SiN$_x$ ARC with a refractive index of $2.05$ at $600$ nm was deposited by the plasmon-enhanced chemical vapour deposition (PECVD) system at $350$°C. The SiO$_2$ space layer and Al back reflector were deposited by the e-beam evaporation. The Ag nanoparticles were formed by annealing the $18$ nm thin Ag film at $200$°C in the nitrogen atmosphere.

To exclude the light loss in the Ag nanoparticles, we measure the reflectance of the standard Al reflector and the plasmonic reflector incorporated with Ag nanoparticles using a glass slide as the superstrate. The results are shown in Fig. 4c. The gap between the two curves is the reflectance loss induced by the particles, which can be the intrinsic absorption in the particles and the plasmon losses in the rough Al back reflector. Assuming only single-bouncing reflection in
As shown in the figure, the contact, produced by thermally growing, could achieve this surface increase for a solar cell with low surface recombination due to the nanoparticles. The \( V_{oc} \) value of the rear plasmonic enhanced cells reduces from 39.2 mA/cm\(^2\) at 180 \( \mu \)m to 19.1 mA/cm\(^2\) at 1 \( \mu \)m, compared with 37.3 mA/cm\(^2\) for the 180 \( \mu \)m standard cells. The energy conversion efficiency \( \eta_{p} \) of the solar cells is calculated by \[ \eta_{p} = \frac{V_{oc} \cdot J_{sc} \cdot FF}{P_{in}} \]

where \( FF \) is the fill factor and \( P_{in} \) the incident power. Fig. 5b shows the efficiency of the rear plasmonic enhanced wafer cells, assuming a reasonable value of \( FF = 80\% \), referenced to the standard 180 \( \mu \)m wafer cells. Through the curves, we can see that 20 \( \mu \)m plasmonic wafer cells realizes the same efficiency (\( \eta_{p} = 18.2\% \)) as the 180 \( \mu \)m standard cells, using only around 10% of the Si material. The wafer thickness can even be further reduced to 3\% (5 \( \mu \)m) of the current 180 \( \mu \)m with a reasonably high efficiency (\( \eta_{p} = 15.3\% \)), which only leads to a moderate decline of approximately 15\%. Unlike most of the efficiency enhancement strategies using silicon surface processing or nanostructuring, which significantly degrade the electrical property of the cells, our method has no impact on the \( V_{oc} \) and \( FF \) and is simple and compatible with the current production procedure\(^{37}\). Therefore there is a high potential to play a role in the further ultra-thin wafer solar cell production.

In conclusion, by using advanced light trapping mechanism with simple but effective metallic nanoparticles, ultra-thin wafer solar cells with ultra-high efficiency are envisage. The experimentally measured large absorption enhancement in nanoparticle-integrated ultra-thin silicon wafer further confirms this predication. Combing the benefit of thinner wafer induced higher \( V_{oc} \), high-efficiency ultra-thin plasmonic wafer cells using a tiny amount of Si material have been demonstrated providing a viable solution for dramatically increased cost-effectiveness for Si wafer solar cells.

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Author contributions

Y.Z., N.S., B.J. and M.G. designed the concept, performed the simulation and the experiments, analyzed the data, and wrote the manuscript. S.F. contributed to the data analysis and the manuscript writing.

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