Surface plasmon mapping of the silver layer in a silicon solar cell using energy-filtered transmission electron microscopy

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The light trapping efficiency of amorphous and microcrystalline thin-film Si solar cells can be optimised by using textured back and front contacts [1]. However, it has been shown that the use of a rough Ag reflector layer results in additional losses through the creation of surface plasmon polaritons [2]. A thin ZnO layer is therefore often introduced between the Ag and n-doped Si layers. Nevertheless, optical measurements show higher parasitic absorption when a rough Ag back reflector is used [3].

Spatially resolved measurements of surface plasmons in metallic nanostructures can be made by using scanning transmission electron microscopy (STEM) combined with electron energy-loss spectroscopy (EELS). Local enhancements of surface plasmon resonances have been shown to depend on the shapes of such nanostructures [4, 5] and on the choice of substrate material [6]. However, point-by-point STEM EELS acquisition is time consuming and has a limited spatial resolution of ~1nm. Energy-filtered transmission electron microscopy (EFTEM) can be used to measure surface plasmon resonances with higher spatial resolution, although with poorer energy resolution than using STEM EELS [7]. In contrast to STEM EELS, mathematical routines have not yet been applied to increase the signal-to-noise ratio and the energy resolution of plasmon maps acquired using EFTEM. The latter approach has also not been used to study working devices or to provide a direct correlation with device properties.

Here, we map the plasmonic absorption of the Ag back reflector layer of a Si solar cell using EFTEM. Energy-loss images were collected using a chromatic and spherical aberration corrected FEI Titan microscope at 300 kV using a Gatan Quantum imaging filter and a monochromated electron beam with a full width at half maximum of 0.3 eV. 80 512×512 pixels images were collected in steps of 0.1 eV using an energy-selecting slit width of 0.2 eV and subsequently aligned in energy to reduce the effects of the non-isochromaticity across the field of view.

Principal component analysis (PCA) was used to reduce noise and a Richardson-Lucy (RL) deconvolution algorithm was applied in the energy direction to reduce the effects of the energy spread of the zero loss peak (ZLP).

When using PCA to separate the contribution of noise from the desired signal, one of the key parameters to consider, is the number of principal components (PCs) to retain. Here, we choose to compute both the reconstructed images (using a given number of PCs) and the residual images (difference images between the original and the reconstructed data).

Figure 1a shows the cumulative distribution function of the amplitude of each pixel in the residual matrix reconstructed using 10, 20, 35 and 50 PCs. These plots provide direct information about the fraction of data that is lost during the PCA process. This information, combined with careful examination of the residual maps, gives an estimate of the PCA-induced information-loss and the amount of noise present in the initial dataset, which cannot be obtained from a simple logarithmic plot of the eigenvalues.

RL deconvolution was then applied to each of the 262144 individual spectra to partially remove the contribution of the ZLP. For comparison, Fig. 1b shows spectra that are (i) as acquired, (ii) after reconstruction using 10, 20, 35 and 50 PCs and (iii) after 10 iterations of the RL algorithm. An improvement in the visibility of the surface plasmon peak is obtained when appropriate numbers of

PC and RL iterations are used. Following these steps, the energies and intensities of selected surface and bulk plasmon modes were determined. The resulting maps are shown in Fig. 2 for a dataset reconstructed with 35 PCs followed by 10 iterations of the RL algorithm are shown figure 2 and are generated automatically by an algorithm that searches for the local maximum amplitude in each given energy range. A clear improvement in the dataset is shown when numerical processing is applied for energies below 3 eV. The surface plasmon resonance and therefore the optical absorption in the visible range can be resolved spatially and used as feedback for the design of the solar cell texture.

References

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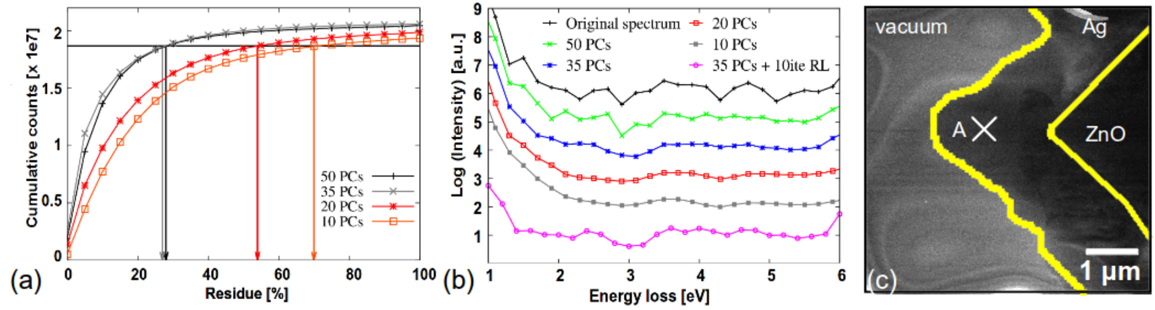

Figure 1. *(a) Cumulative distribution function of the residual matrix (values of the residual matrix are normalized by the intensity of the reconstructed matrix and expressed in percent) reconstructed using 10, 20, 35 and 50 PCs. The horizontal line represents 90% of the total pixel numbers (i.e. 90% of 512x512x80). The arrows show the percentage of information lost by 90% of the pixels. (b) Original EEL spectra, spectra reconstructed using 10, 20, 35 and 50 PCs and spectra obtained after applying 10 iterations of the RL algorithm to data reconstructed with 35 PCs obtained from position A in (c). (c) EFTEM image (1.2 ± 0.5 eV) of the Ag back reflector layer, deposited on top of a 2 µm thick ZnO layer.*

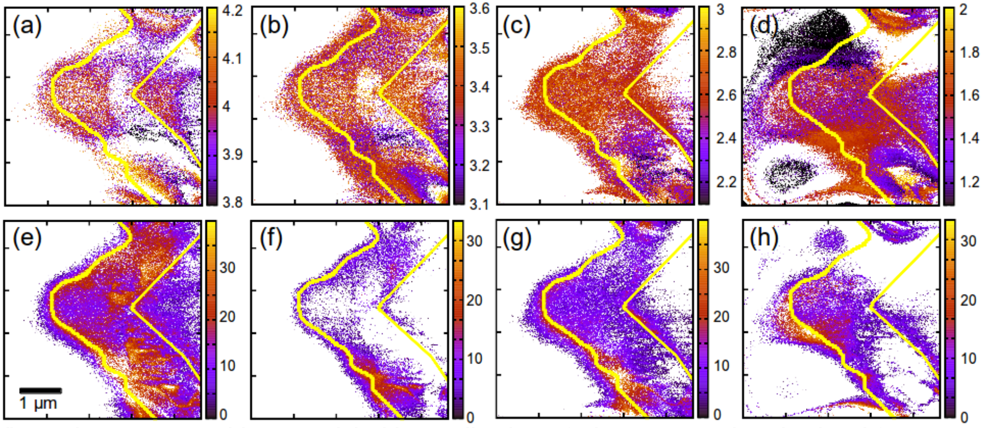

Figure 2. *(a-d) Peak energy positions and (e-h) amplitudes of plasmon peaks obtained from an EFTEM image series of the Ag reflector layer in a Si solar cell reconstructed using 35 PCs and 10 iterations of the RL algorithm. (a, e) correspond to the bulk Ag plasmon peak, while the remaining maps are for surface plasmon peaks centred on (b, f) ~3.4 eV (365 nm), (c, g) ~2.7 eV (460 nm) and (d, h) ~1.6 eV (776 nm). The energy scales are in eV. The amplitudes are shown in arbitrary units. The yellow lines represent the Ag/vacuum and Ag/ZnO interfaces. The peaks in vacuum for figures (d)-(h) have low intensities and are due the achromatic aberrations of the GIF. The white colour indicates the absence of peaks.*