Plasmonics in hybrid solar cells

The success of photovoltaics (PVs) requires critical advances in material studies and cell-design concepts to increase device performance, reduce the manufacturing, installation, and operation cost. Presently, through the optimization of device processing and the use of suitable materials, the state-of-the-art efficiency of solar cells has been rapidly enhanced. To pave the way for the viable and practical application of solar cells, the technology is still urgently under development. One strategy towards light management has been acknowledged as an essential issue in achieving higher efficiencies. Many trapping strategies for solar cells have been explored, such as optical spacers, photonic crystals, and folded device architectures. Plasmonics includes various aspects of surface plasmons, which are electromagnetic surface waves that utilize light-metal interactions. More recently, novel metallic nanostructures using surface plasmons have been demonstrated as a promising approach for enhancing the performance of solar devices. In applications, surface plasmon polaritons (SPPs) and the near field from localized surface plasmon resonance (LSPR) are beneficial to light absorption as well as to the electrical characteristics of the solar cells.

They are strongly confined at the interface of metal/dielectric or semiconductor, with light scattering, near-field enhancement, and plasmon-induced charge separation mechanisms for enhancement in solar cells. It has been shown that the utilization of

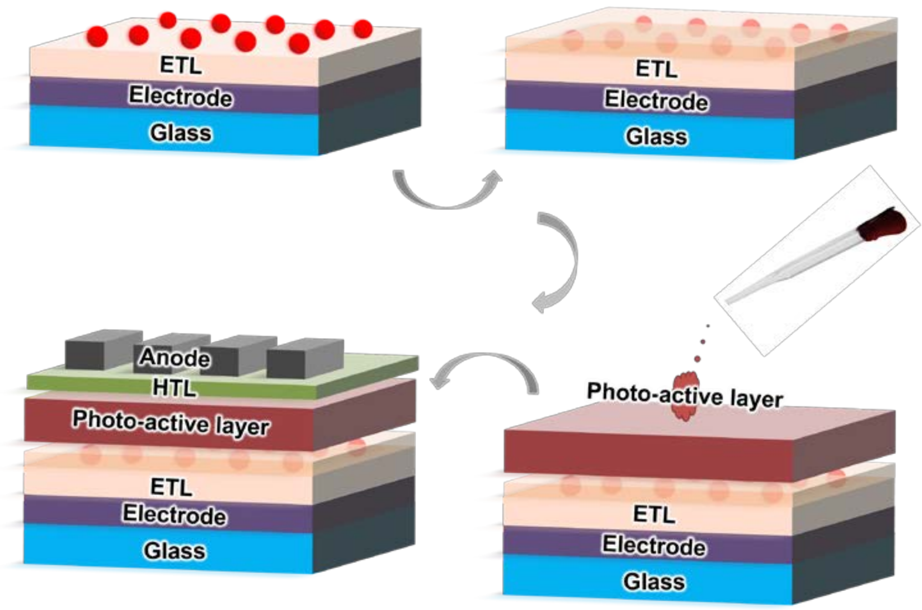

Figure 1. Schematic diagram of the plasmonic metal nanoparticles enhanced photovoltaics

plasmonic metal nanoparticles (NPs) is frequently proposed as a means to further enhance the light absorption in the broad wavelength range as well as facilitate charge collection and transportation of the devices. In particular, the use of metallic nanostructures has been investigated in almost all types of solar cells, as is shown in Figure 1, such as organic solar cells (OSCs), perovskite solar cells (PSCs), dye-sensitized solar cells (DSSCs), quantum dot solar cells (QDSCs).

For solar cells, it is possible to achieve enhanced broadband, polarization, and angle independent absorption by incorporating plasmonic nanostructures. Metal nanocrystals with facile tunability of their optical properties have shown great potential as an optical engineering tool in solar cells by modifying their constitution, size, morphology, and surrounding materials. In the past decades, many types of plasmonic NPs (e.g., Au, Ag, Al, Cu, etc.) have been incorporated either between interfaces or in photoactive layers, which used to explore the potential benefits for performance enhancement in solar cells. However, there is still limited effect in terms of a systematical fundamental study and fabrication novelty of plasmonic structures in plasmonic enhanced photovoltaics. Therefore, it is of crucial importance to fabricating suitable plasmonic nanostructures and investigate their fundamentals in solar cell devices.

In our group, we have investigated metal nanoparticles on polymer and semiconductor interfaces with advanced scattering methods. For example, we fabricated a gradient nanoparticle-polymer multilayer and investigated its morphology by micro-beam grazing incidence small-angle x-ray scattering (μ-GISAXS) [1]. We also studied the isolated nanoparticle to coalescent layer transition in a gradient sputtered gold nanoparticle multiplayer by μ-GISAXS [2]. The two-dimensional assemblies of metal nanoparticle structures we characterized using GISAXS and we correlated structure and optoelectronic properties in the two-dimensional nanoparticle assembly [3]. Meanwhile our group extended these studies e.g. to the tailoring of the optical properties of sputter-deposited gold nanostructures on nanostructured titanium dioxide templates, as they would be used in DSSCs.

To further study the properties of plasmonic structures and their applications in solar cells, the precise modulation of metallic nanostructures with tunable plasmonic effects is planned to be achieved based on the self-assembly technique. In our work, we fabricated plasmonic structures through facile and scalable methods, as is shown in Figure 2, that could enable integrate the highly-dispersed plasmonic metal NPs into solar cells. Advanced scattering methods such as grazing incidence small-angle x-ray and neutron scattering (GISAXS and GISANS) are used to further investigate the mechanisms of plasmonic structure application. With the in-depth exploration of the plasmonic structures, we believe that the plasmonic nanostructures application in solar cells is an essential issue in pushing higher performance.

Featured publications:

1. S.V.Roth, M.Burghammer, C.Riekel, P.Müller-Buschbaum, A.Diethert, P.Panagiotou,

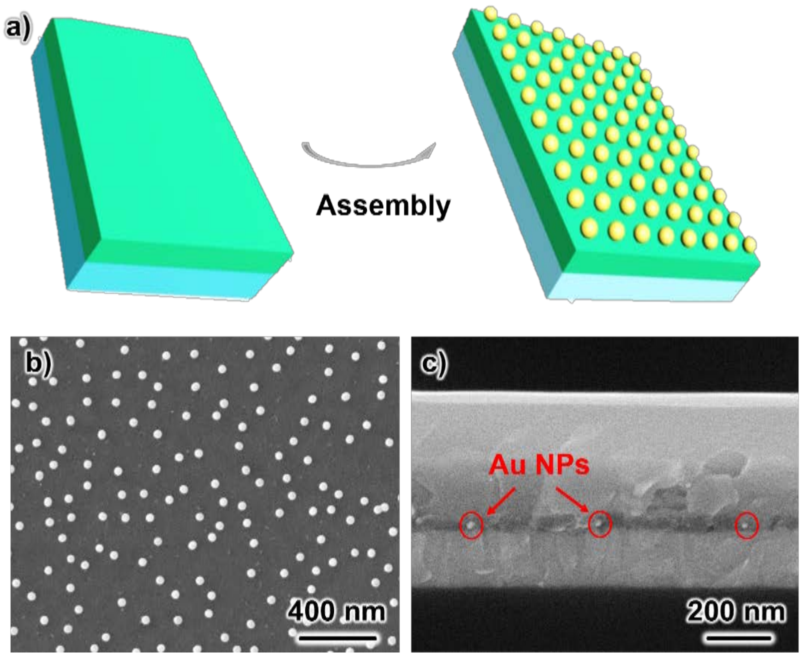

Figure 2. Schematic diagram and SEM images of the plasmonic metal nanoparticles self-assembly.

H.Walter
Self-assembled gradient nanoparticle-polymer multilayers investigated by an advanced characterisation method: Microbeam grazing incidence x-ray scattering*;* *Appl. Phys. Lett*. **82**, 1935-1937 (2003)

2. S.V.Roth, H.Walter, M.Burghammer, C.Riekel, B.Lengeler, C.Schroer, M.Kuhlmann, T.Walther, R.Domnick, P.Müller-Buschbaum
Combinatorial investigation of the isolated nanoparticle to coalescent layer transition in a gradient sputtered gold nanoparticle multiplayer*;*

Appl. Phys. Lett. **88**, 021910 (2006)

3. M. A. Mangold, M. A. Niedermeier, M. Rawolle, J. Perlich, S. V. Roth, A. W. Holleitner, P. Müller-Buschbaum

Correlation between structure and optoelectronic properties in a two-dimensional nanoparticle assembly;

Phys. Stat. Sol. (RRL) **5**, 16-18 (2011)

4. S. Liang, W. Chen, S. Yin, S. J. Schaper, R. Guo, J. Drewes, N. Carstens, T. Strunskus, M. Gensch, M. Schwartzkopf, F. Faupel, S. V. Roth, Y. Cheng, P. Müller-Buschbaum

Tailoring the optical properties of sputter-deposited gold nanostructures on nanostructured titanium dioxide templates based on in situ grazing-incidence small-angle x-ray scattering determined growth laws

ACS Appl. Mater. Interfaces **13**, 14728-14740 (2021)