Plasmonics in nanostructured Si solar cells

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Plasmonics, the electronic response of light interacting with metal nanostructures, is a promising novel concept in the quest for photovoltaic devices with high efficiencies with low cost materials[1 2]. Interest in plasmonics, which merges optics with electronics[3 4] at very small scales, has increased considerably since about a decade. The potential of plasmonics in photovoltaics is recognized and there has been a considerable research effort in this field. Five main effects are distinguished with the metal plasmon and optically active neighbouring materials[5]: **1) Plasmonic field enhancement**[6 7 8 9], (a near-field effect) increases the electromagnetic field close to the metal surface by orders of magnitude. This is the result of dipole radiation of the metal nanoparticle in response to illumination. This is particularly interesting for thin film solar cells as light concentration has a significant effect on the overall absorption. **2) Scattering (**a far field-effect) at/by the metal nanoparticle[10] increases the light path length in a solar cell and is therefore an important mechanism to increase efficiency. Incident light is scattered off the object into a distribution of optical modes within the semiconductor. **3) Coupling** of plasmon resonance to waveguide modes in thin semiconductor slabs. **4) The coupling of an emitter to plasmon modes** also affects both the radiative and non-radiative decay rates. This phenomenon is based on the principle that the strength with which an emitter couples with an electromagnetic field depends on its environment[11 12 13]. **5) Energy transfer** from the absorber/emitter to plasmon modes of a nearby nanoparticle can occur by for example Forster Energy Transfer (FRET) [14] or vice versa. This energy will be partially dissipated or coupled to radiation[15 16]. The balance between these effects depends strongly on the geometry, shape, size and distance[17]. One of the first experimental investigations of plasmonic enhancement for photovoltaics involved silver

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nanoparticles in an organic solar cell[18 19]. In the system (ITO/metal-clusters/CuPc/In) it has been shown that the incorporation of copper or gold clusters increases the photocurrent by a factor of more than two. The first papers to explore the potential of localized surface plasmon resonance (LSPR) in solid state photovoltaics were published in the late 1990s by Stuart and Hall[20]. Their device consisted of a thin silicon-on-insulator wafer, where the Si was 165 nm thick, and since the absorbing Si layer was separated from the Si substrate by a layer of SiO_2, it acts as a thin waveguide. Metal island formation was achieved by depositing a thin metallic film and annealing under N_2 so that the film coalesced into discrete islands. A recent work by Barnard et al.[21] shows the enhancing effect of silver nanostructures on photocurrent in silicon. Underneath a metal nano-antenna the field intensity is enhanced by a factor of 2.8 while locally the field enhancement can be significantly higher (up to 20) in “hotspots” under the corners of the antenna. A theoretical study of nanoparticles for solar cells shows that an absorption increase of 10-15 % is easily feasible[22].

In this lecture the above will be discussed with respect to recent plasmon-solar cell results from our own group. In this novel approach of a nano-engineered plasmonic back reflector which scatters strongly, light is coupled into guided modes of an ultra thin 160 nm a-Si:H solar cell[23]. In this work an increase of the external quantum efficiency (EQE) between 600 and 800 nm of about 8% was observed due to metallic nano-patterns. The spatial order of patterned nanostructures has a strong effect on its plasmonic performance[24]. With systematically designed pseudorandom arrays of nanostructures based on their power spectral density, the spatial frequencies are correlated with measured and simulated photocurrent. Integrated cell designs consisting of patterned plasmonic back reflectors and a nanostructured semiconductor top interfaces give broadband and isotropic photocurrent enhancement. An example of a viable nanostructured three-dimensional solar cells employing an ultrathin hydrogenated amorphous silicon a-Si:H n-i-p junction uses a zinc oxide nanorod arrays as substrate[25]. The ZnO nanorods were prepared by aqueous chemical growth at 80 °C. The photovoltaic performance of the nanorod/a-Si:H solar cell with an ultrathin absorber layer of only 25 nm is yields an efficiency of 3.6% and a short-circuit current density of 8.3 mA/cm2, significantly higher than values achieved for planar or even textured counterparts with three times thicker absorber layers.

Plasmonic interaction with an a-Si:H solar cell is also investigated by growing the active layer around a silver nanoneedle. Its plasmonic response to incident light is investigated by measuring the photocurrents as a function of wavelength, incidence angle and polarization. The experimental results are compared with Finite Difference Time Domain (FDTD) calculations.

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