

Harvesting of infrared solar energy by thermoplasmonic nanoantenna for enhanced photovoltaic-thermoelectric systems

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Abstract: Our work aims at using thermoplasmonic nanoantennas to create a photothermal interface able to effectively absorb infrared radiation from the sun and generate heat. This interface could then be integrated to increase the efficiency of hybrid photovoltaic-thermoelectric systems. Numerical simulations were used to identify an optimal design by studying the impact of the material, geometry and dimensions on the optical and thermal properties of the nanoantenna. First demonstrators of nanostructured photothermal interfaces were then fabricated and characterized.

The performances of photovoltaic (PV) cells have grown over the years to reach energy conversion efficiencies as high as 30 % for the most recent single-junction solar cells [1]. However, further improvement of these devices is hindered by their intrinsic limitations. Indeed, standard single-junction photovoltaic cells do not absorb photons with an energy lower than their bandgap, while photons of higher energy are partially thermalized, resulting in limited photovoltaic conversion and an increase in the cell's temperature. In order to take advantage of these thermal losses, PV cells can be combined with a thermoelectric generator (TEG). The energy conversion efficiency of the resulting hybrid photovoltaic-thermoelectric (PV-TE) devices has been shown to be higher than that of the sole PV cell [2-4]. Yet, the low energy photons, which are not absorbed nor thermalized by the PV cell, remain unexploited. For example, a GaAs cell with a band gap of 1.42 eV is transparent to photons with a wavelength higher than 875 nm, which represent 35 % of the incoming solar power. In order to optimize the efficiency of PV-TE systems, an interesting approach consists in adding a photothermal layer in-between the PV cell and TEG [5-6]. Its role is to absorb IR photons and convert their energy into heat to increase the power output of the TEG.

This work is focused on the design of a photothermal interface based on thermoplasmonic nanoantennas. Such interface should exhibit a high optical absorption over the 0.875 – 2.5 μm wavelength range as well as a high photothermal conversion, while being electrically insulating and thermally conductive. In order to target the optimal structures in terms of infrared solar light harvesting, we calculated the optical properties of several nanoantennas with different shapes, sizes and compositions, using numerical simulations based on the discrete dipole approximation method, see Figure 1.A. We show that it is possible to identify efficient photothermal nanoantennas. We found that nickel-based nanoantenna with a diabolo-like shape have infrared absorption power density as high as 0.8 nW/ μm^2 . To go one step further, we have implemented a photo-thermal heat diffusion model to estimate the temperature increase that could be reached with such antennas. We show that a photothermal interface of highly absorbing diabolo nanoantennas could possibly heat up by 6°C under IR solar irradiation.

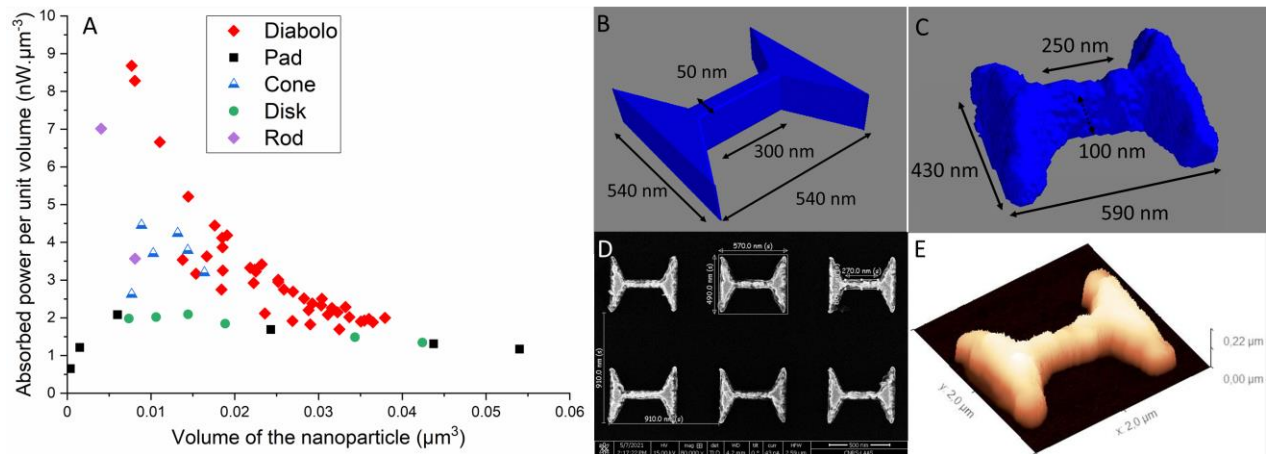


Figure 1. A: Calculated solar absorption over 0.875-2.5 μm for ideal isolated nickel nanoantennas of different shapes. Comparison between the simulation target of a perfect diablole (B), and a realistic target (C) based on the topological characteristics extracted from SEM (D) and AFM (E) images of Ni diabolos fabricated by electron beam lithography.

Then, arrays of selected antennas were created using nanofabrication techniques. Their morphological, optical and thermal properties were characterized and compared to the simulated perfect structures. In particular, we investigated the impact of the defects (roughness, size variation...), due to the fabrication process using SEM and AFM-based topological data to generate realistic targets (see Fig. 1.B-E) for the numerical simulations. Finally, we will discuss the impact of the substrate, the collective effects (interaction between antennas), the spatial ordering of the nanoantennas, and their encapsulation, on the performances of a complete photothermal interface. Our work points out the crucial parameters for the design of nanoantenna-based photothermal interface implemented in hybrid PV-TE systems.

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