Harvesting of IR solar energy by thermoplasmonic nanoantennas

Sébastien Hanauer, Adnen Mlayah, Franck Carcenac, Jean-Baptiste Doucet, Emmanuelle Daran, Alexandre Dmitriev, Inès Massiot

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[1]Laboratoire d'Analyse et d'Architecture des Systèmes (LAAS-CNRS), 7 Avenue du Colonel Roche, 31400 Toulouse, France
[2]Department of Physics, University of Gothenburg, 41296 Göteborg, Sweden
Contact: shanauer@laas.fr

Context

Mono-junction photovoltaic cells have intrinsic limitations:

- Non-absorption of low energy photons (<Eg);
- Thermalization of high energy photons (>Eg);
- Heating of the cell while operating, which reduces its efficiency.

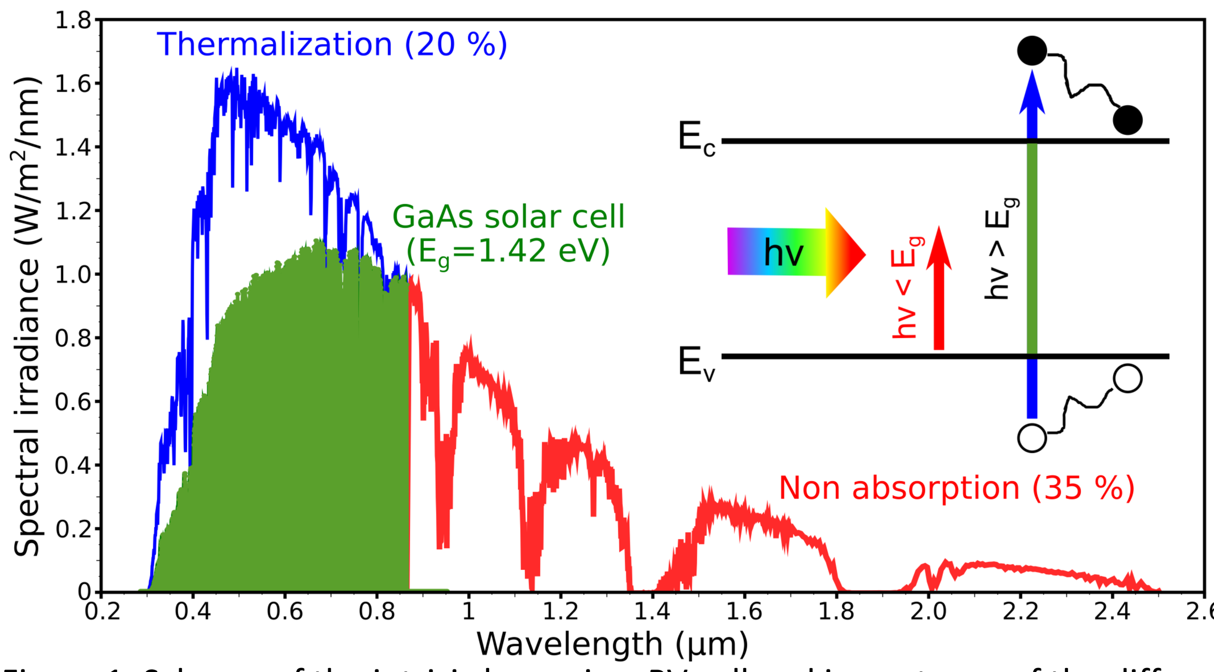

Figure 1: Scheme of the intrisic losses in a PV cell and importance of the different phenomena for a GaAs cell with regard to the AM 1.5G solar spectrum.

Hybrid photovoltaic-thermoelectric (PV-TE) devices have been shown to increase the energy conversion efficiency by compensating the thermal losses in a PV cell [1-3].

Several studies aimed at optimizing the efficiency of PV-TE by including a **photothermal interface** (PTI) in between the PV cell and the thermoelectric generator [4-5].

Objective of the PhD: to design a PTI using thermoplasmonic nanoantennas to convert solar IR radiation into heat.

Characteristics of an optimal PTI:

- High absorption and matching with the solar IR spectrum;
- High thermal conductivity;
- Electrically insulating.

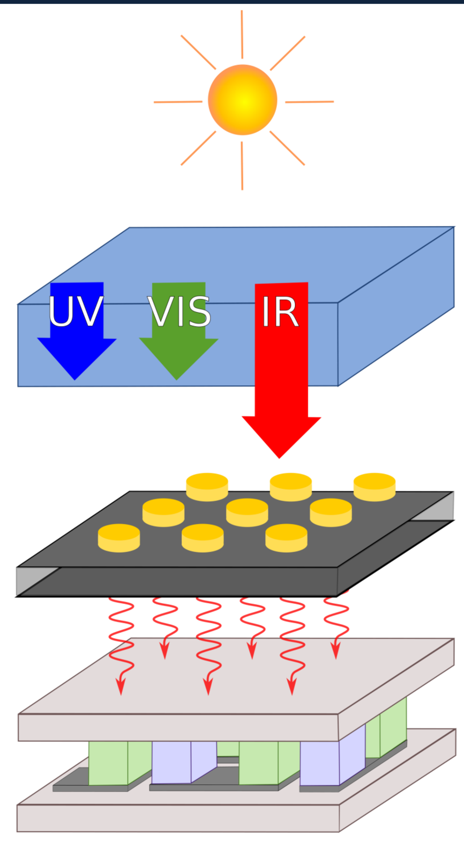

Figure 2: Schematic representation of a PV-TE device including a photothermal interface made of thermoplasmonic nanoantennas.

Optical simulations

Perfect structures

We use numerical simulations to study isolated nickel nanoparticles of different shapes and sizes, in order to find the structure which is best suited for IR solar harvesting.

- The absorption and scattering cross-sections of these particles are extracted from discrete dipole approximation (DDA) calculations, using the open-source code *DDSCAT* [6].
- The absorption spectra are compared to the AM1.5G spectrum to calculate the absorbed solar power over the range 0.875-2.5 µm.

All nanoparticles have a height of 150 nm.

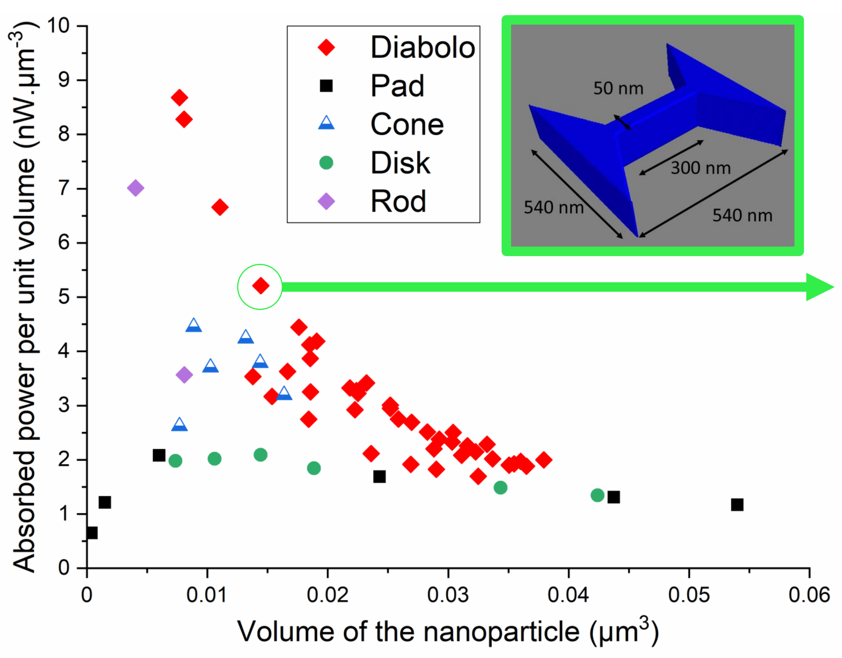

Figure 3: Calculated solar absorption over the range 0.875-2.5 µm, normalized by volume, for isolated nickel nanoantennas of different shapes. The circled entry corresponds to the presented diabolo.

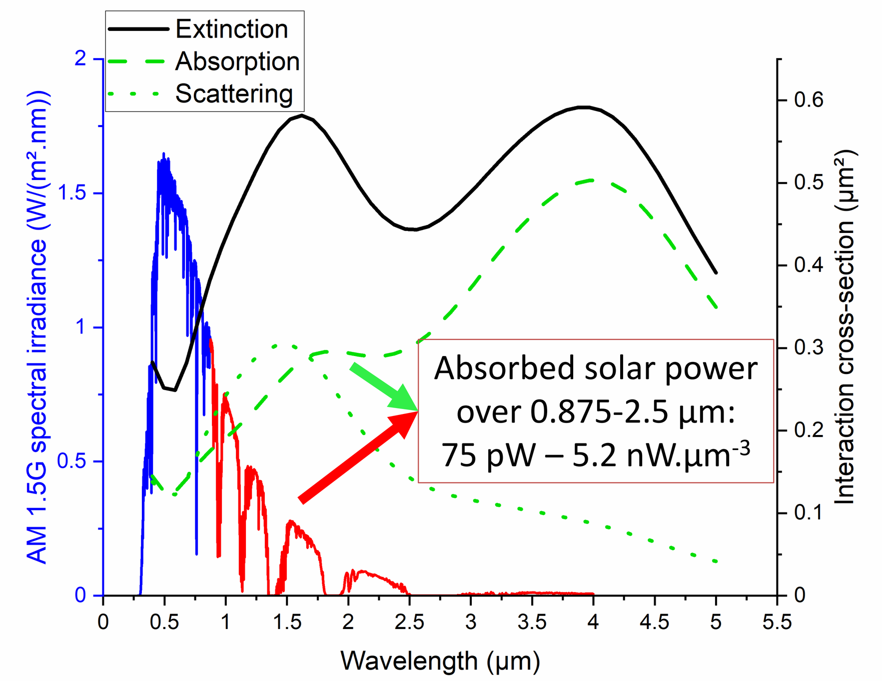

Figure 4: Calculated interaction cross-sections for a perfect Ni diabolo and AM 1.5G solar spectrum, below (red) and above (blue) the energy gap of a GaAs PV cell.

Smaller nanoparticles tend to have a better absorption-to-volume ratio.

Choice of Ni diabolo as a promising structure.

Realistic structures

We developed a process to fabricate Ni nanoantennas on Si substrate using e-beam lithography, and study the impact of the fabrication defects.

- SEM and AFM characterization to reconstruct the surface topology of a real particle
- DDA simulations on the realistic structure

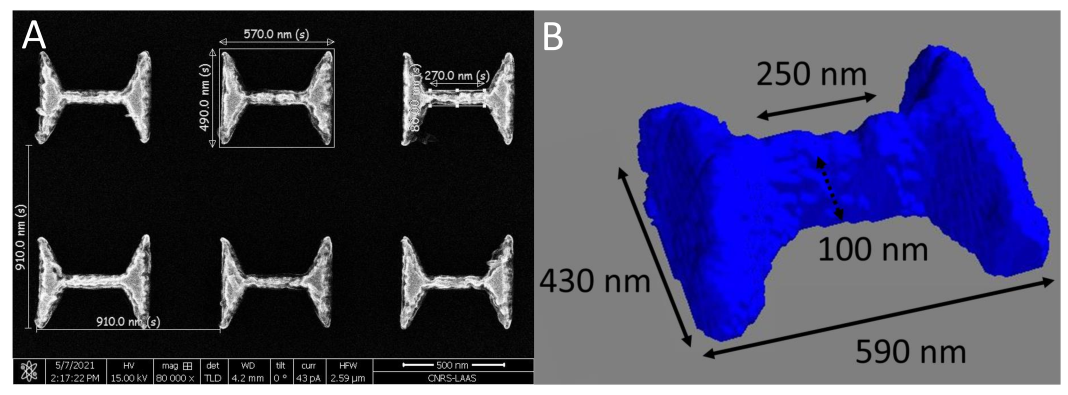

Figure 5: (A) SEM image of Ni diabolos on Si and (B) Simulation target extracted from AFM measurements to represent a real Ni diabolo.

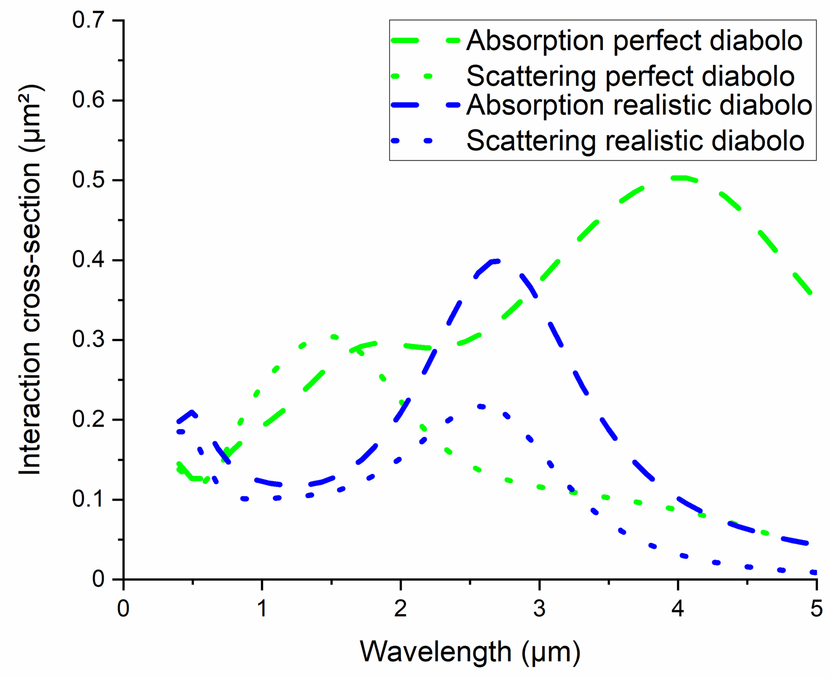

Figure 6: Comparison between the interaction cross-section spectra of a perfect Ni diabolo and the associated realistic structure.

Shift of the absorption peaks when switching from perfect to realistic structure, due to:

- Surface roughness
- Change in the dimensions

Absorbed solar power over 0.875-2.5 µm:

- Perfect: 75 pW – 5.2 nW.µm^{-3}
- Realistic: 46 pW – 2.5 nW.µm^{-3}

Important impact of the fabrication defects on optical properties.

Poor spectral matching between absorption and solar irradiance.

Thermal model

What is the temperature elevation that could be expected for a photothermal interface under IR solar illumination ?

Model of a photothermal interface on a TEG

- Absorption by a 2D array of perfect Ni diabolos (75 pW each) - **85 % surface coverage**
- Illumination: solar IR (λ < 875 nm)
- Ambient temperature: $T_{amb} = T_0 = 20$ °C
- Substrate of the PTI: Si
- Commercially available TEG

Temperature gradient through the TEG:

- **6 °C for perfect diabolos**
- **4 °C for realistic structures**

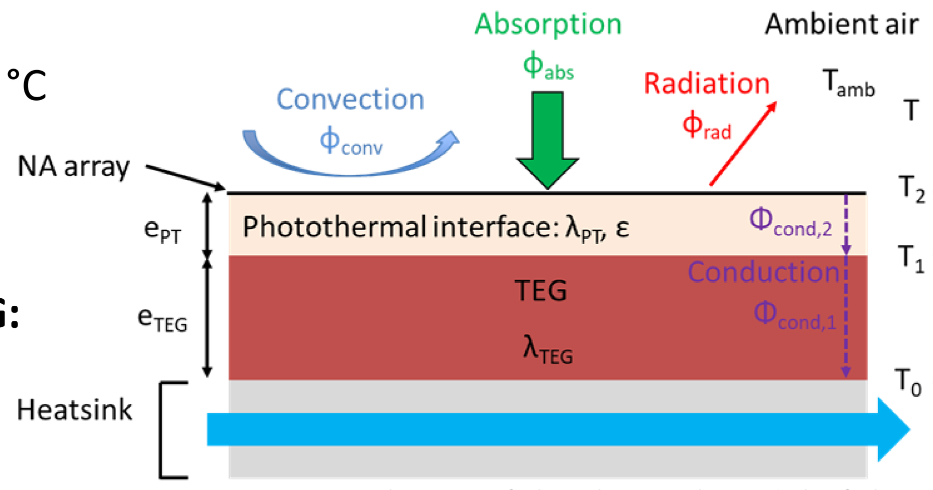

Figure 7: Scheme of the thermal model of the PTI+TEG system showing the thermal fluxes.

Conclusion & perspectives

- Identification of a nanoantenna design capable of efficient IR solar harvesting.
- Development of a proven process to fabricate metallic nanoantennas on various substrate (Si, glass), and study of the fabrication defects:
  - Need to optimize the dimensions of the fabricated nanoantennas;
  - Working on alternative fabrication processes (electrochemical deposition, nanoimprint) to reduce the surface roughness or the fabrication time.
- The thermal model can be improved to estimate the temperature of a photothermal interface integrated in a hybrid PV-TE device.
- The optical and thermal properties of the PTI need to be experimentally characterized:
  - IR spectroscopy;
  - Measure of localized heating using Raman spectroscopy.

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Acknowledgment: this work was partly supported by the French RENATECH network.