# Photothermal conversion of solar infrared radiation by thermoplasmonic nanoantennas for hybrid photovoltaic-thermoelectric devices

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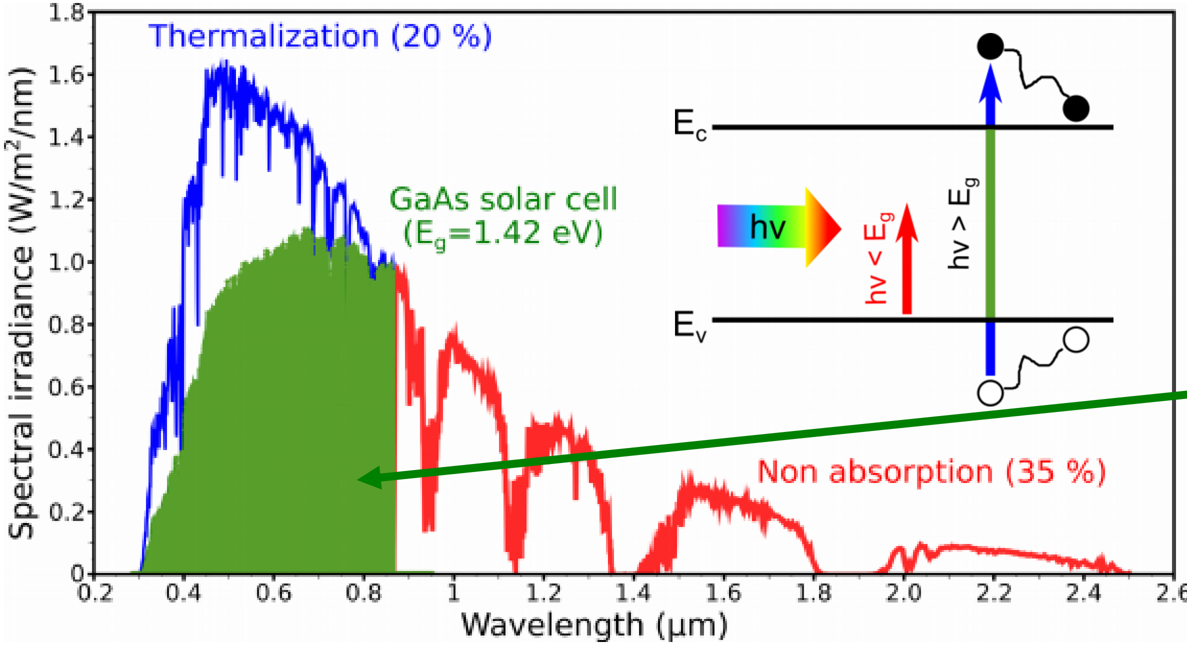
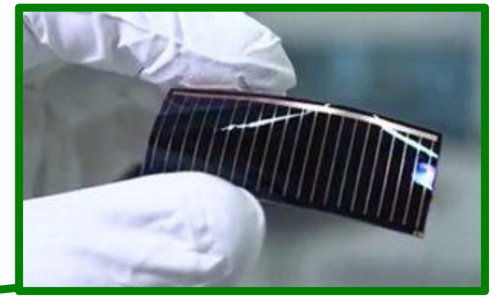
# Motivation: intrinsic limits of solar cells

> Conversion efficiency of mono-junction solar cell is limited



GaAs 29.1 %

> **Challenges:**

- Exploit a broader spectral range
- Harvest the waste heat in the solar cell

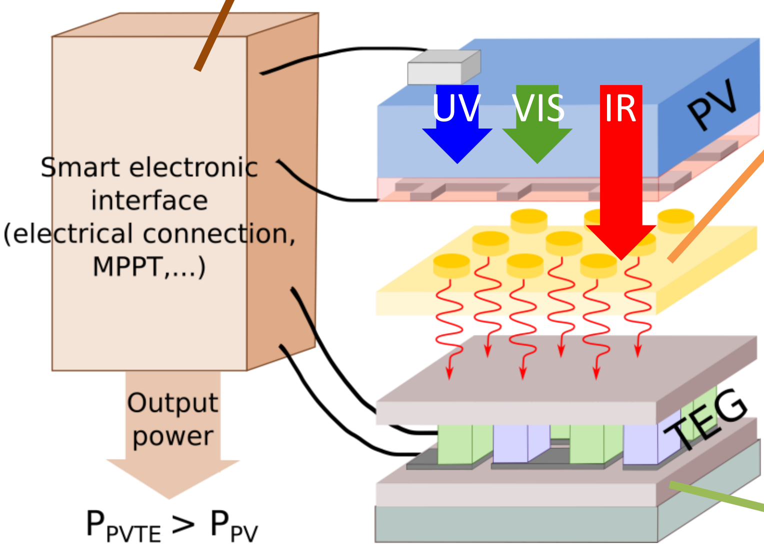
> No absorption of low energy photons)

> Partial thermalization of high energy photons

# Custom photovoltaic-thermolectric device

**ANR project HYDRES (2022-2025):**
LAAS, Institut Jean Lamour / Univ. Lorraine, Nancy

**Model of the complete system** including PV-TE interface + electronic interface




**Plasmonic photothermal antennas** to boost the TEG efficiency

**Technological fabrication process for high thermal coupling**

**Design & fabrication of custom TEG**

> Characteristics of an optimal interface:

- High absorption in the IR range
- High thermal conductivity
- Electrical insulation

# Work on the photothermal interface

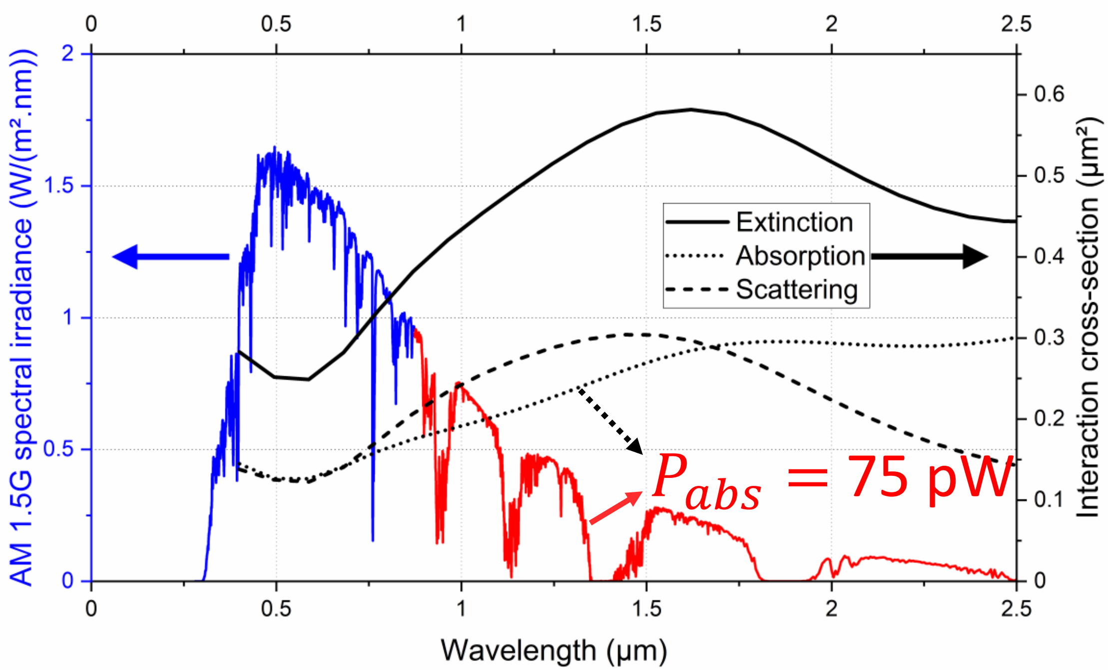
> Objective: to design an efficient photothermal interface based on plasmonic nanoantennas

> Method:

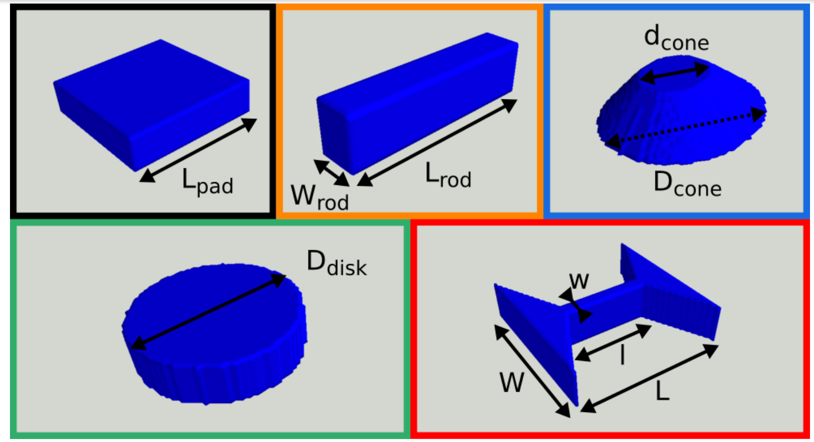
- Numerical simulation of isolated nanoantennas
- Technological fabrication
  - Electron-beam lithography
  - Hole-mask colloidal lithography
- Characterization
  - FTIR spectroscopy
  - IR thermometry

# Optical simulations of isolated nanoantennas (NAs)

- DDA method to simulated the optical response of **nickel** NAs
  - Different shapes and dimensions
  - Constant height: H=150 nm




*Calculated optical response of a diabolo-shaped NA compared to the solar spectrum*

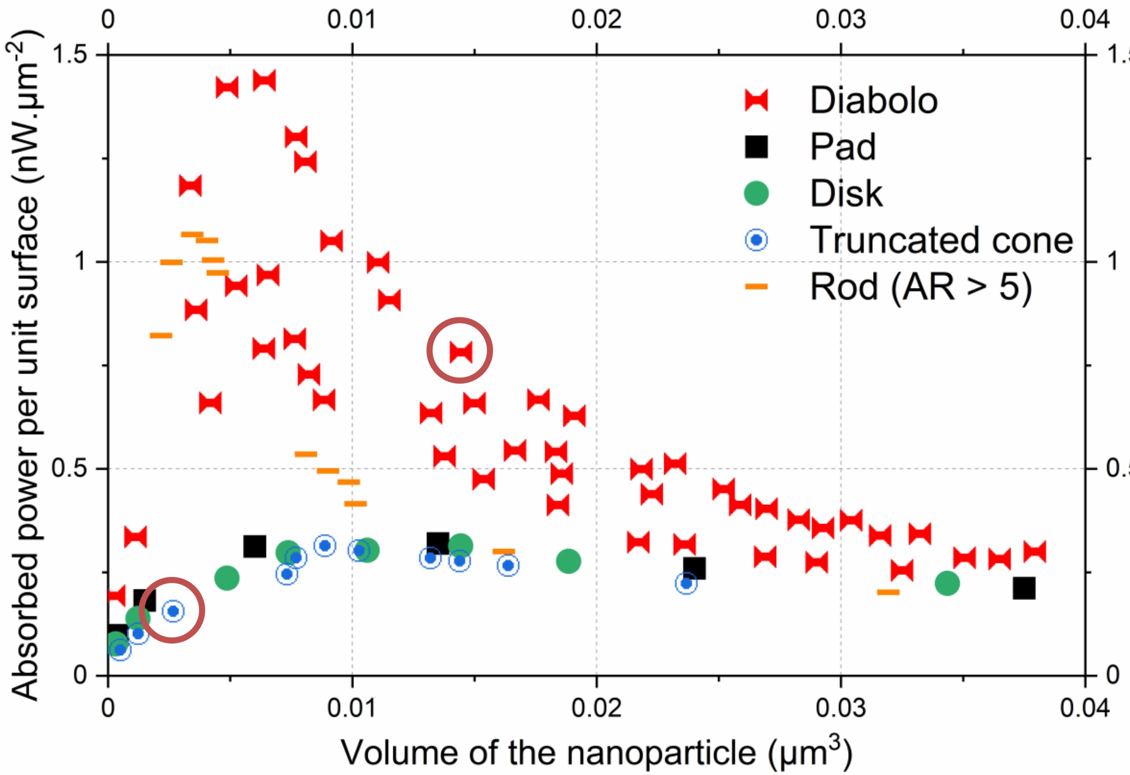


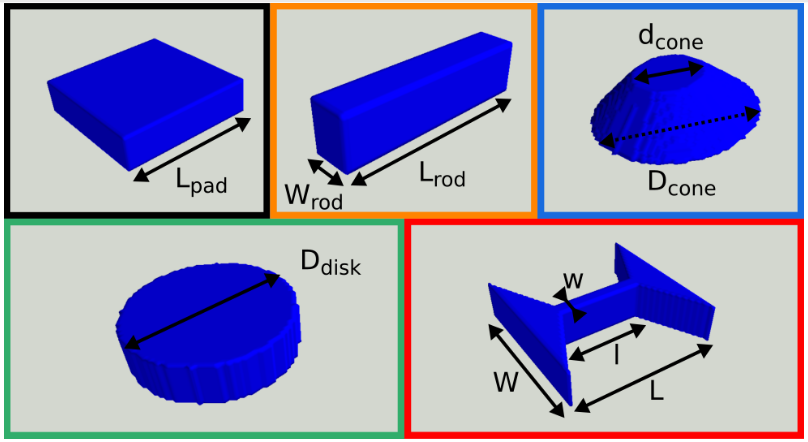

- Quantification of the **spectral matching** between
  - Absorption cross-section $\sigma_{abs}$
  - AM1.5G solar spectrum $\phi$

- **Power absorbed** by a NA under solar IR illumination
  - $P_{abs} = \int_{0.875\ \mu m}^{2.5\ \mu m} [\sigma_{abs}(\lambda)\phi(\lambda)]d\lambda$

# Choice of the optimal nanoantenna geometry

> For a given geometry:
- Smaller volume ➔ less absorption ($\sigma_{abs} \propto V$)
- Larger volume ➔ more diffusion ($\sigma_{scat} \propto V^2$)
- Change in size ➔ shift of absorption peaks




> Diabolos have the best absorption/surface ratio
- Good spectral matching
- Higher absorption intensity

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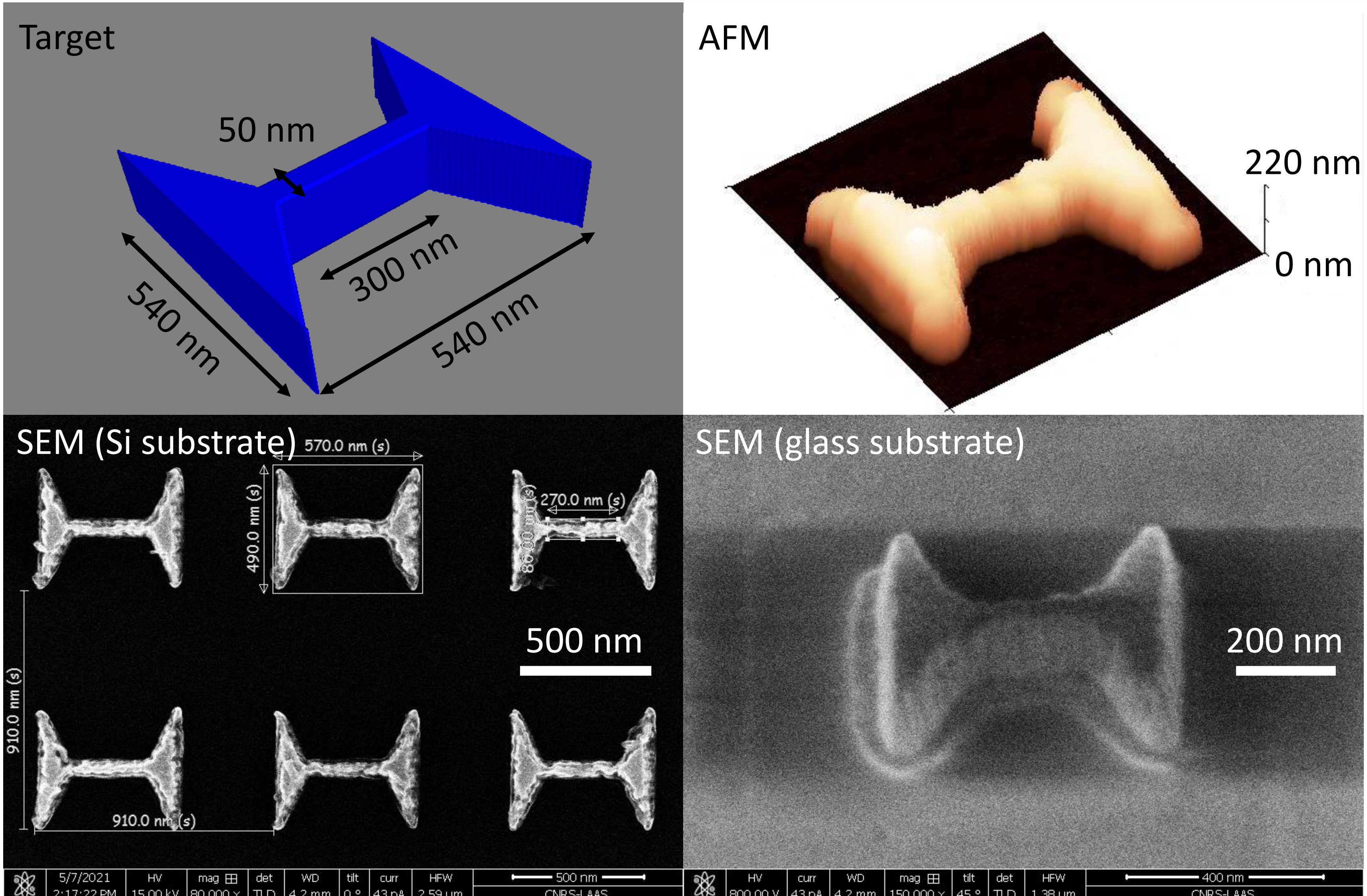
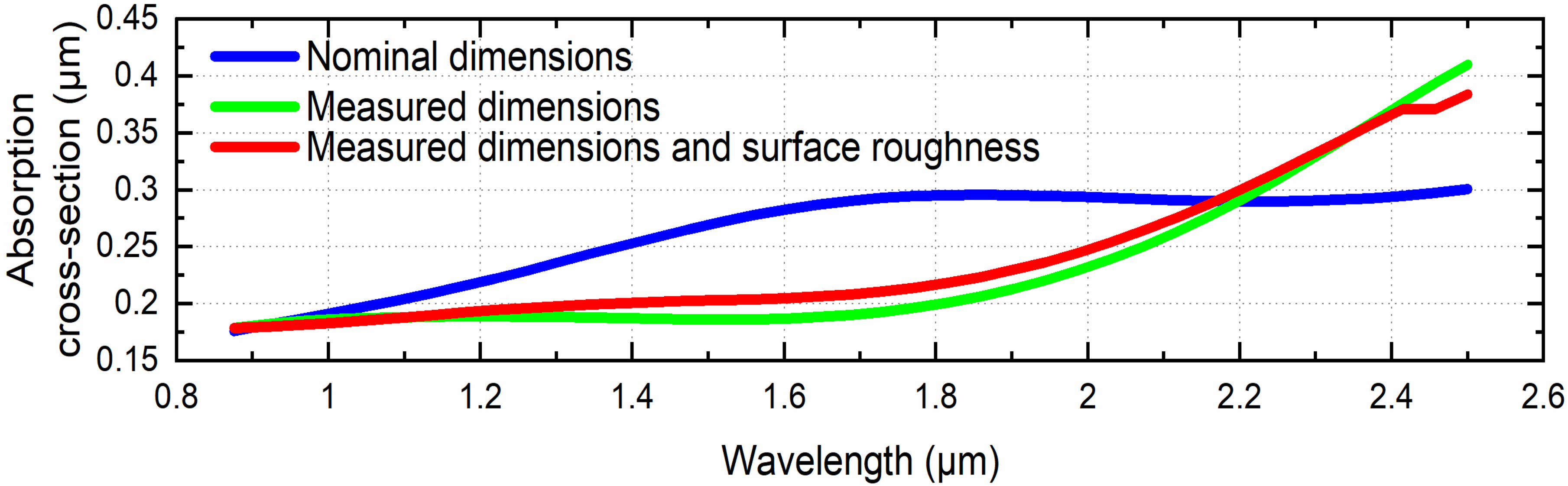
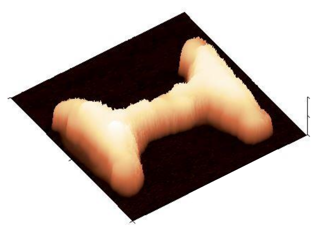
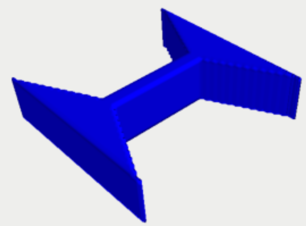
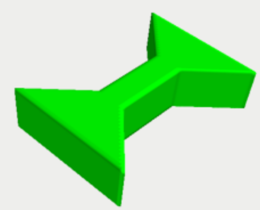
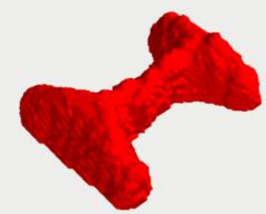
# Diabolo-shaped NAs by electron-beam lithography



# Calculated impact of fabrication defects

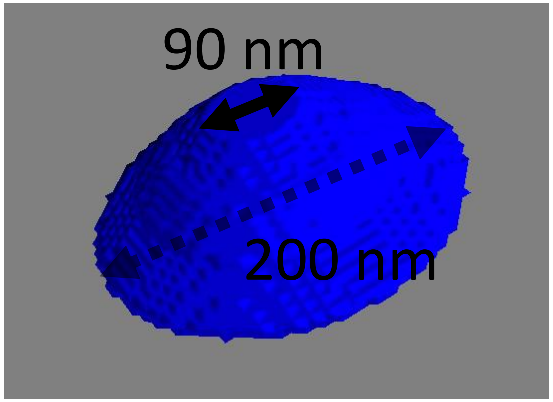


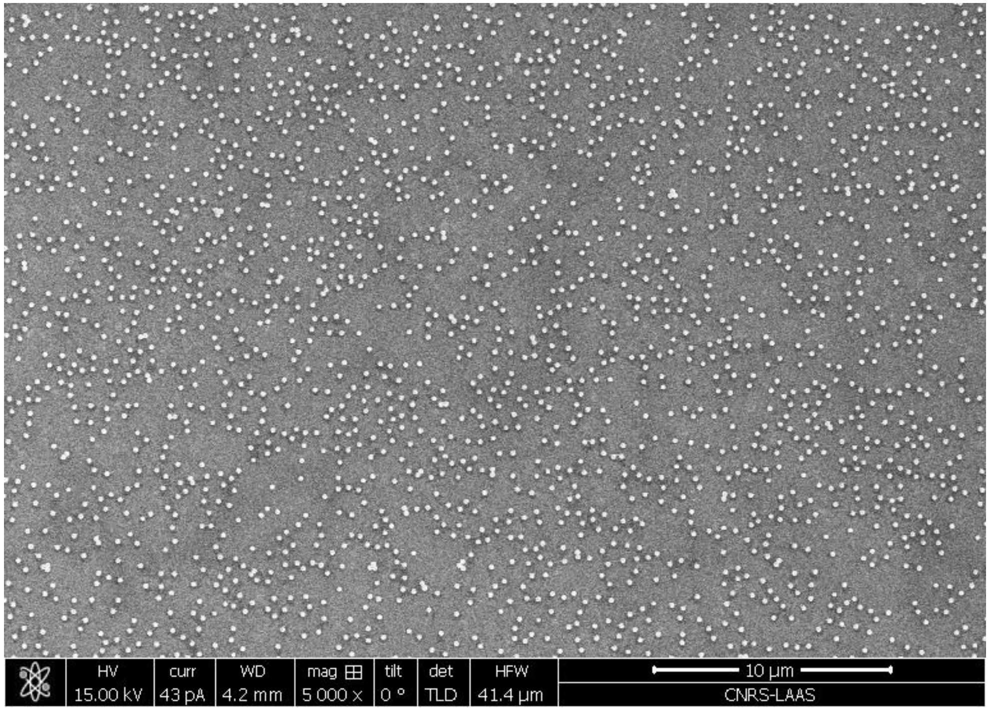

|  |  |  |  |
|---|---|---|---|
| Absorbed solar power (pW) | 75 | 66 | 67 |
| Absorption per unit surface (nW.µm$^{-2}$) | 0.78 | 0.53 | 0.44 |
| Absorption/scattering ratio | 0.89 | 0.61 | 0.76 |

*S. Hanauer et al., to be published*

# Nanocone surface by colloidal lithography

- Self-assembly of beads via electrostatic interactions
  - Disordered pattern with short-range order
  - Control of the density through electrostatic charges
  - Fast patterning over large areas – low cost – few geometries – limited pattern control
- Truncated cones with a base diameter and a height of 200 nm



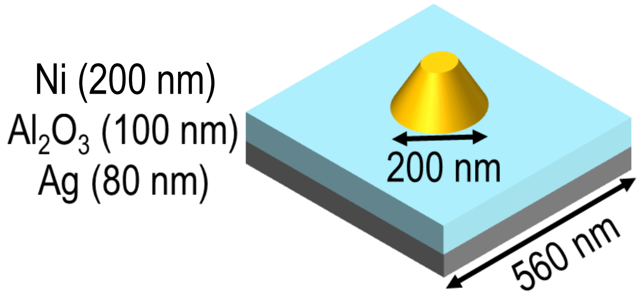



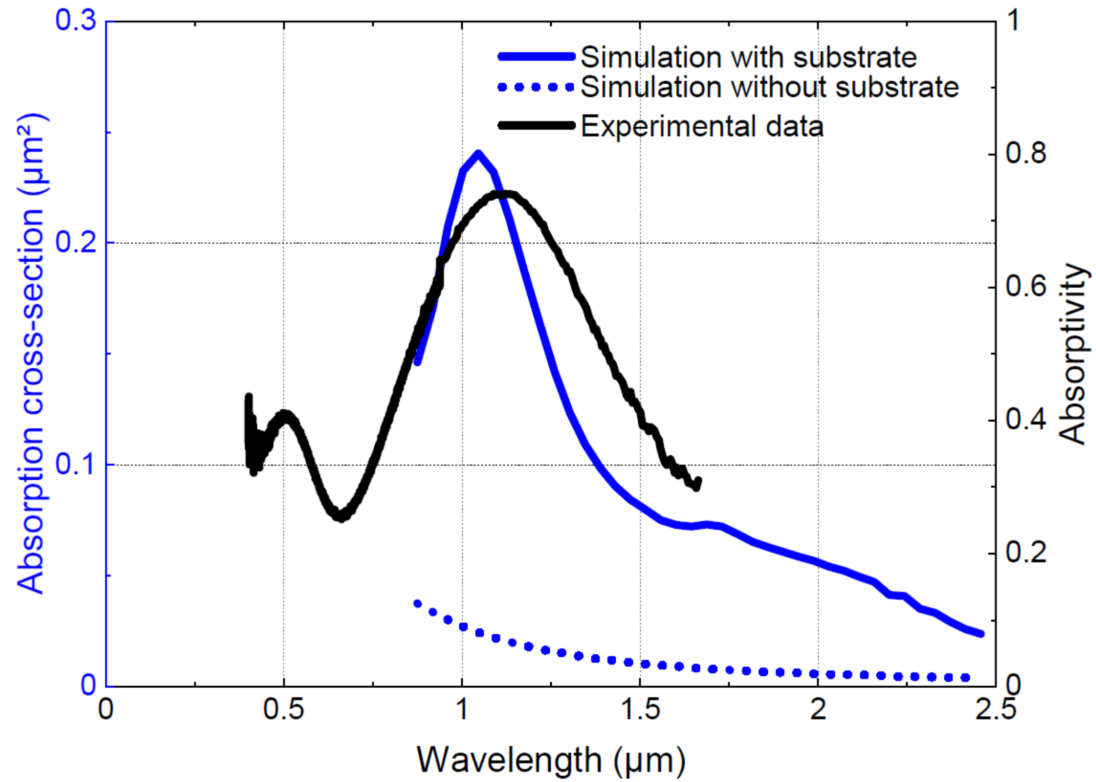

SEM (Mag 5 000x)

- Substrate: glass/Ag/$Al_2O_3$
- Surface coverage: 10 %

# Absorption of nanocones on substrate

- DDA simulation of a particle on Ag/$Al_2O_3$ substrate
  - Strong impact of substrate on optical properties

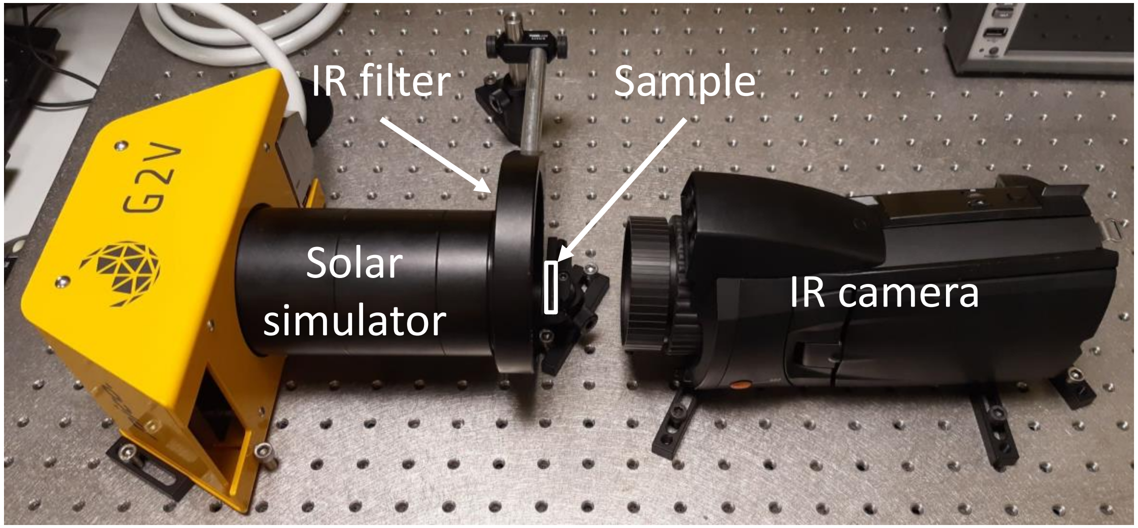


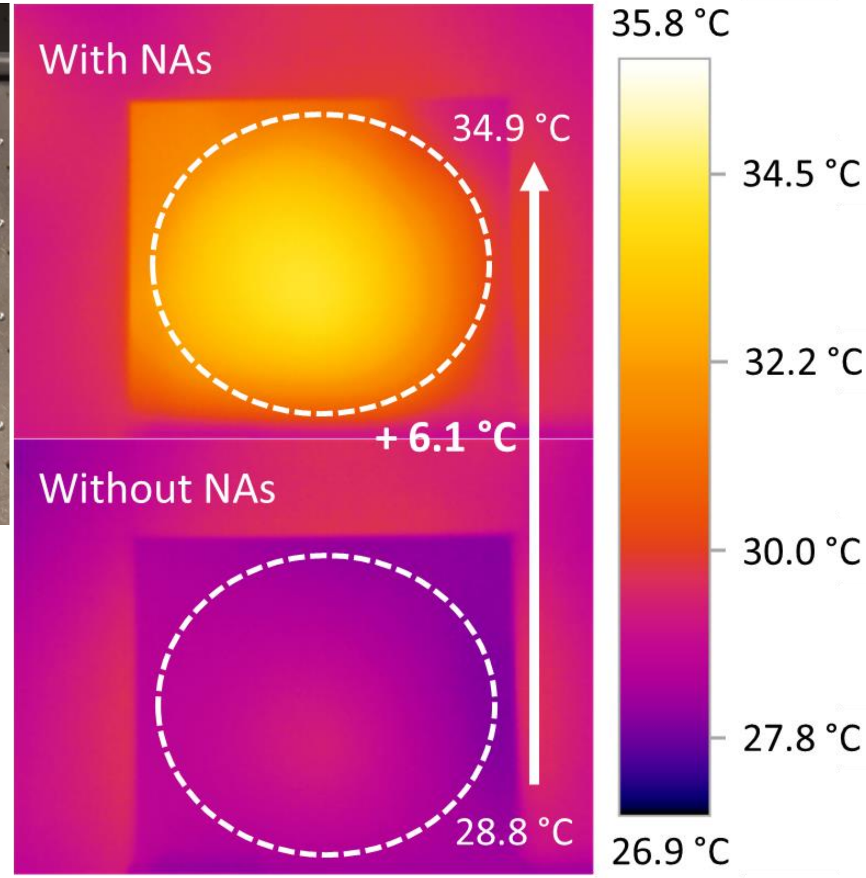




- FTIR spectroscopy on the fabricated sample
- Good agreement between calculated absorption and experimental spectrum
  - Widening of the experimental peak due to size dispersion
- Absorption over the 0.875-1.5 µm range: 150 W/m²

# Experimental setup for temperature measurements

> Heating of the colloidal lithography sample



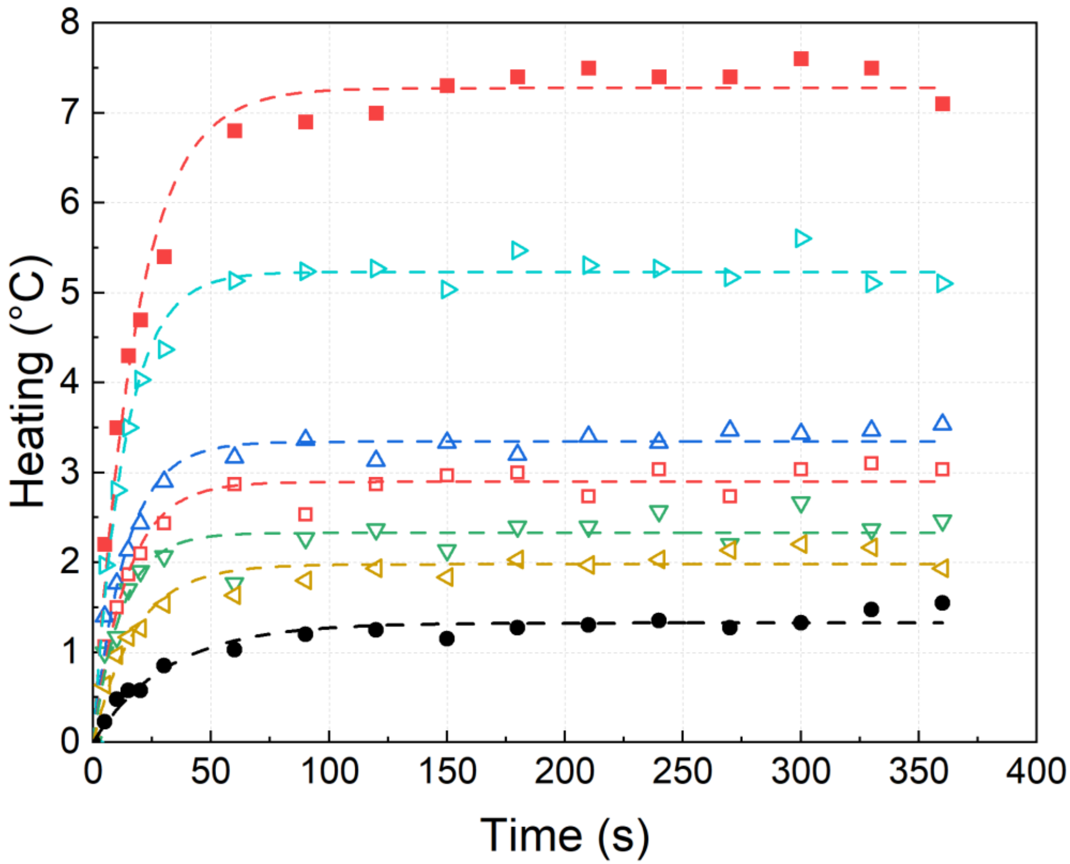




> Illumination spectra:
- Solar IR (875 – 1500 nm)
- 250 W/m²

> +7.3 °C as compared to ambient temperature

Temperature without illumination: 27.5 °C

# Temperature increase for different materials




- Measurement of the surface coverage (FF) by SEM
- IR thermometry under solar simulator
- $\Delta T_{cone} = (T_{sample} - T_{ref}) * \frac{S_{cone}}{FF * S}$

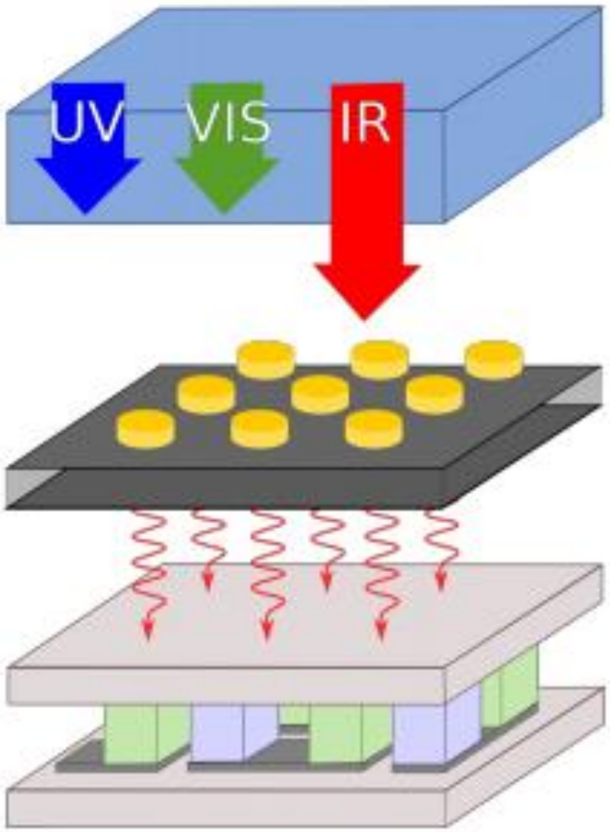
| | Surface coverage | ΔT per cone |
|---|---|---|
| Al | 5.8 % | 15 nK |
| Ni (200) | 10.1 % | 13 nK |
| Ni (50) | 4.6 % | 8 nK |
| Au | 7.2 % | 3 nK |
| Ag | 8.2 % | 2 nK |

*S. Hanauer et al., to be published*

# Conclusion and perspectives

> Demonstration of a nanoantenna-based photothermal interface for PV-TE hybrid devices
- Experimental temperature increase of 7.3 °C under solar IR illumination
- Possibility to reach >10 °C increase with diabolo-like particles and higher density

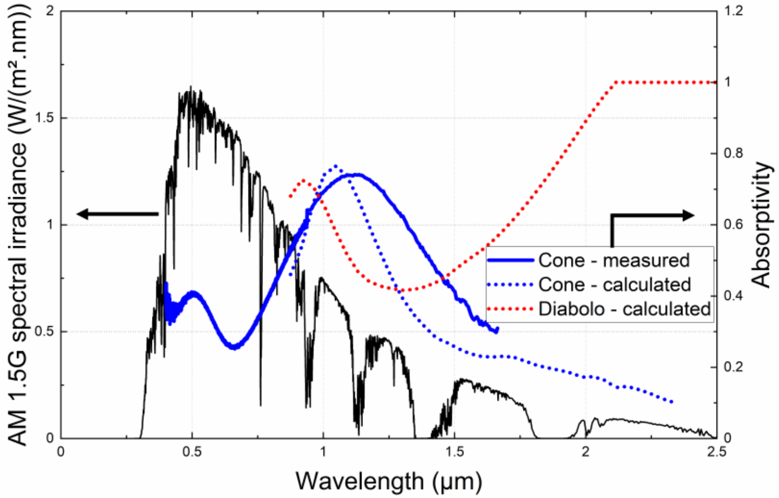
> Towards the integration in a PV-TE device
- Impact of substrate and encapsulation
- Opto-thermal characterization of a PV-PTI-TE device



# Thank you for your attention

# Heating estimated by an analytical model

- DDA-based numerical simulations of
  - Diabolo and cone;
  - With and without substrate (10% coverage);
  - Over the 0.875-1.5 and 0.875-2.5 µm range.
- Experimental measurement of the absorption spectrum and temperature increase under solar illumination for the cone

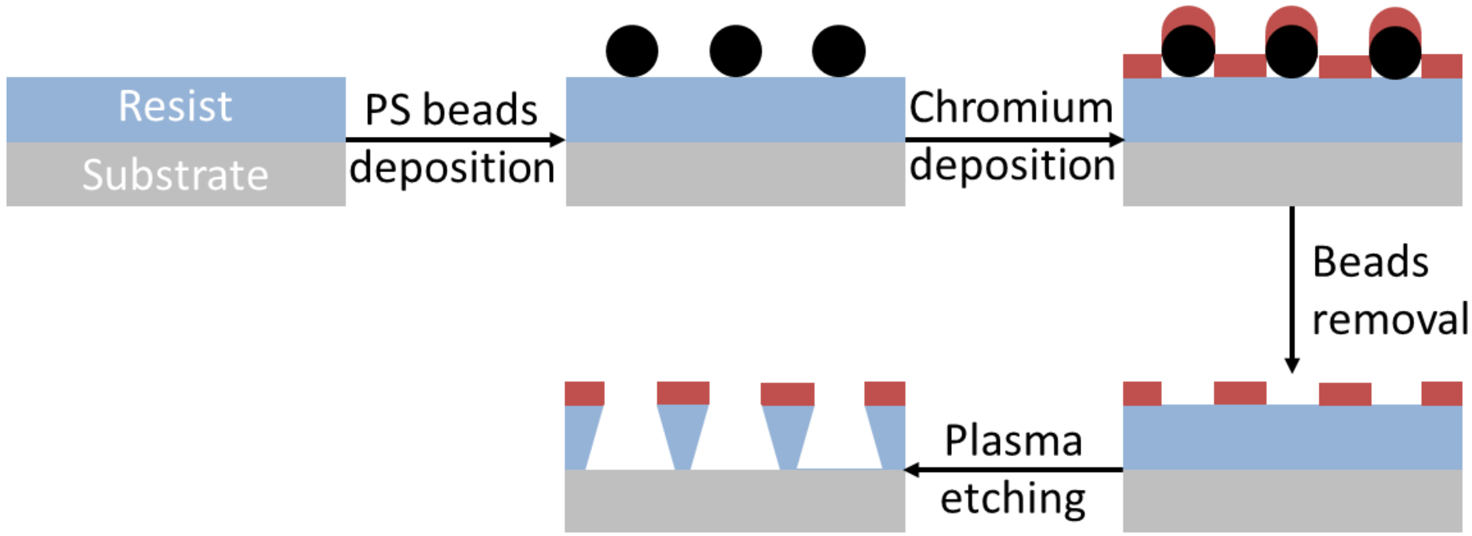



- Estimation of the temperature of diabolo-covered samples under solar IR illumination

| | Calculated absorbed power of isolated particle | | Calculated absorbed power of particle on substrate | | Measured absorption | Temperature increase | |
|---|---|---|---|---|---|---|---|
| Range (µm) | 0.875–1.5 | 0.875-2.5 | 0.875–1.5 | 0.875-2.5 | 0.875-1.5 | 0.875-1.5 | 0.875-2.5 |
| Cone | 4.4 pW<br>140 W/m² | 5 pW<br>160 W/m² | 44 pW<br>141 W/m² | 50 pW<br>160 W/m² | 49 pW<br>156 W/m² | + 7.3 °C | + 7.5 °C |
| Diabolo | 48 pW<br>534 W/m² | 75 pW<br>782 W/m² | 113 pW<br>133 W/m² | 170 pW<br>196 W/m² | ? | + 6.2 °C | + 9.1 °C |

# Hole-Mask Colloidal Lithography (HCL)

- Deposition of polystyrene (PS) beads on the resist
  - Negatively charged PS beads in water
  - Positively charged resist




- Large area (up to 6 inch)
- « Low-cost »

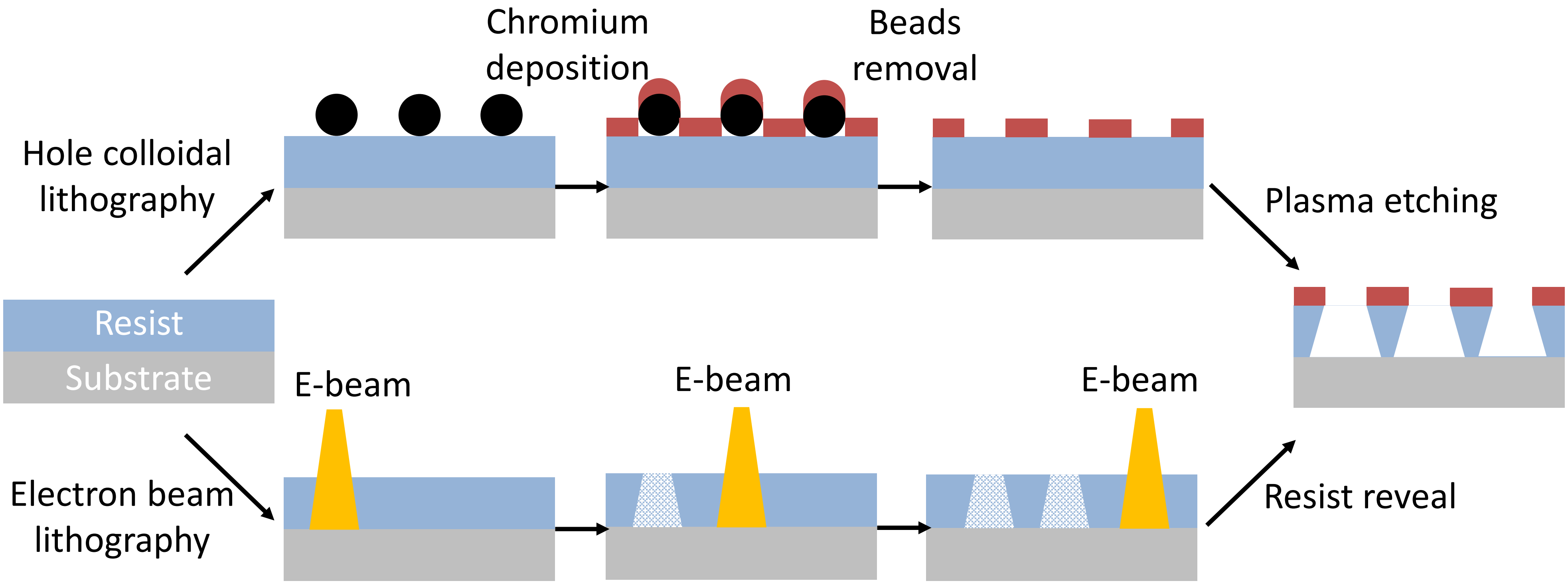
- Few geometries accessible
- Limited control over the pattern order

- Soon available at LAAS

# Fabrication of nickel particles on glass substrate

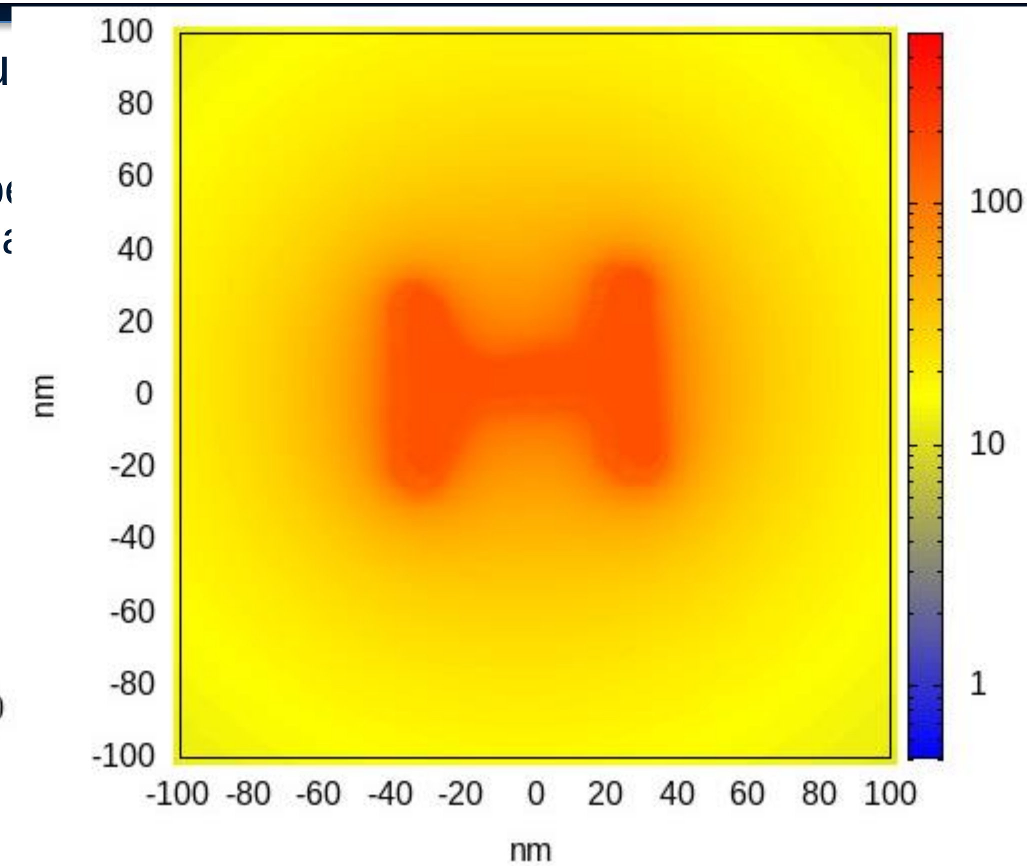
## > 2 fabrication techniques

- Hole colloidal lithography (HCL): fast - large area – few geometries - limited pattern control
- Electron beam lithography (EBL): pattern precision – resolution – time-consuming - costly



# Thermal calculations

- Based on the results of previou optical simulations
  - Hypothesis: 100% of the absorb solar power is converted into hea
- Calculation of the steady-state temperature distribution for a particle on a substrate
  - Substrate: glass

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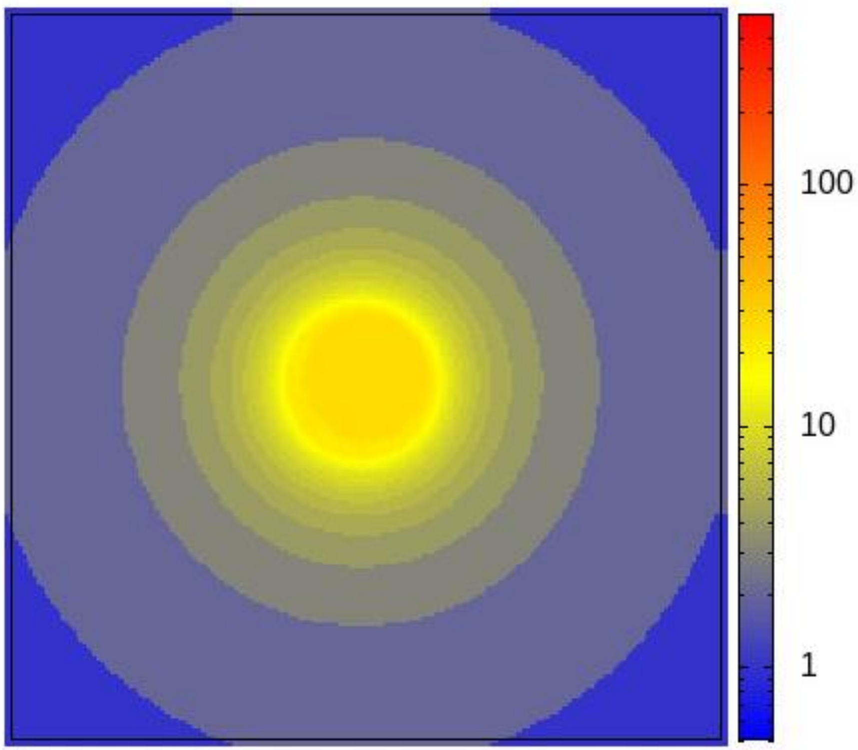


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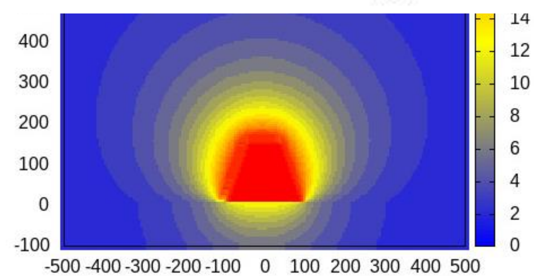


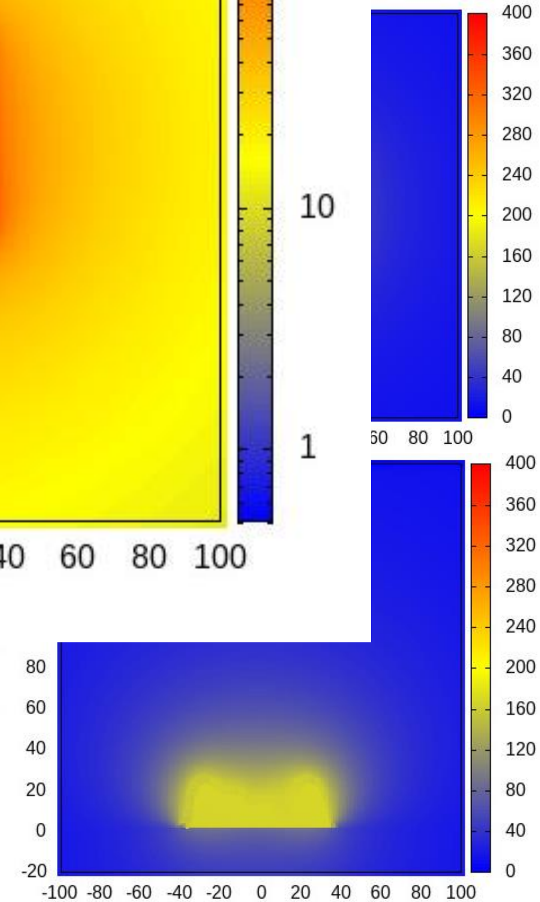

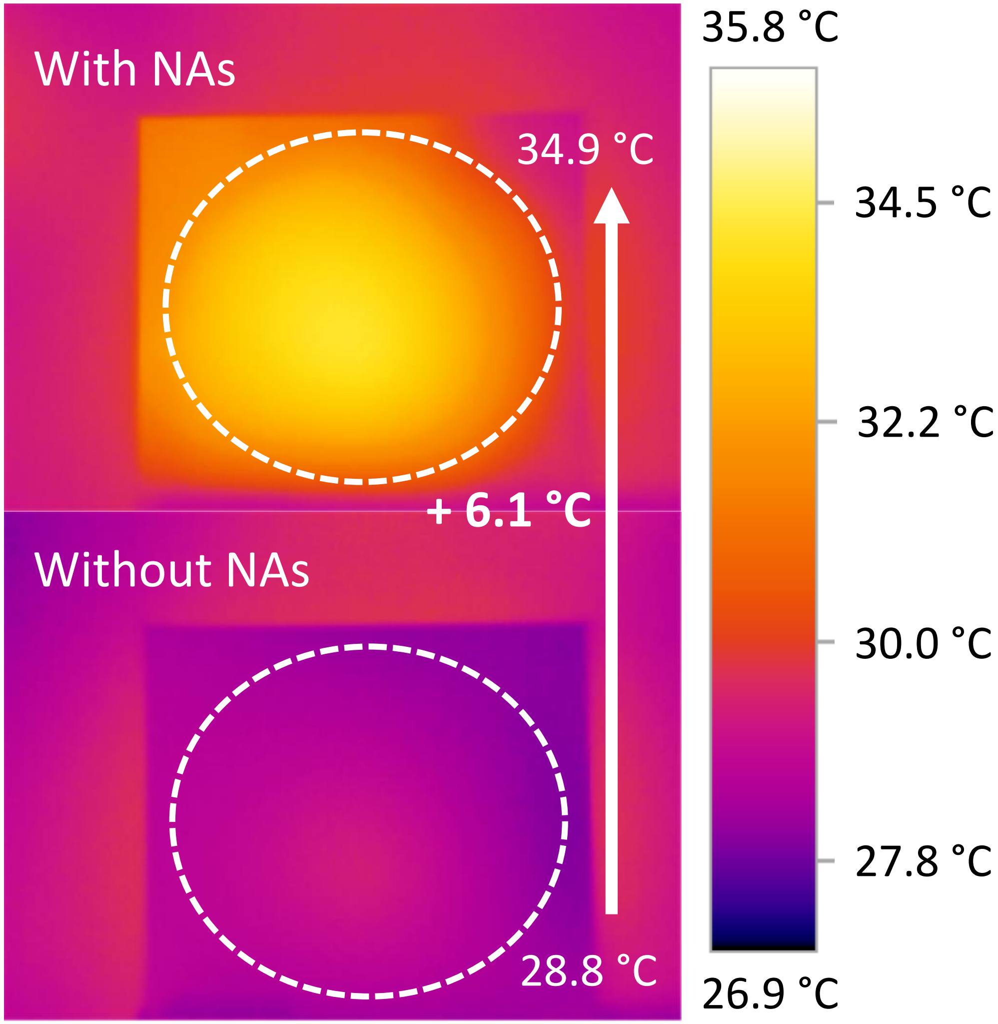
With NAs
34.9 °C
+ 6.1 °C
Without NAs
28.8 °C
35.8 °C
34.5 °C
32.2 °C
30.0 °C
27.8 °C
26.9 °C

# Conclusion and perspectives

> Summary

- Study of the optical properties of isolated nanoantennas with different shapes and dimensions
- Fabrication of arrays of nanoparticles on glass substrate
- Experimental and numerical temperature characterization
  - Heating results from a collective effect

> Future work

- EBL fabrication on larger areas
- Optical characterization of the samples
- Integration in a PV-TE device