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Thermal Emission From Silicon Microspheres

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Abstract

Silicon is the base semiconductor of the current microelectronic industry and the material of choice for visible light detection and harvesting. Some years ago we introduced a new process to produce highly spherical silicon microspheres that we usually call "silicon colloids". This material, thanks to its smooth surface, present very well defined Mie resonances and is able to efficiently trap light in the visible and IR, opening the door to manifold applications in electronics, photonics, cosmetics, and paints, among others.

Silicon microspheres can be used for optimized absorption, exhibiting $q_{abs}>1$, while the large dwell time of photons at the resonating frequencies can boost absorption even at the bandgap edge. Here we propose to use (doped) silicon microspheres for enhanced thermal radiation in the MIR. We are developing a set-up to measure the thermal radiation from a single sphere. We expect to find an emission cross section superior to one (antenna effect) at frequencies around the atmospheric window.

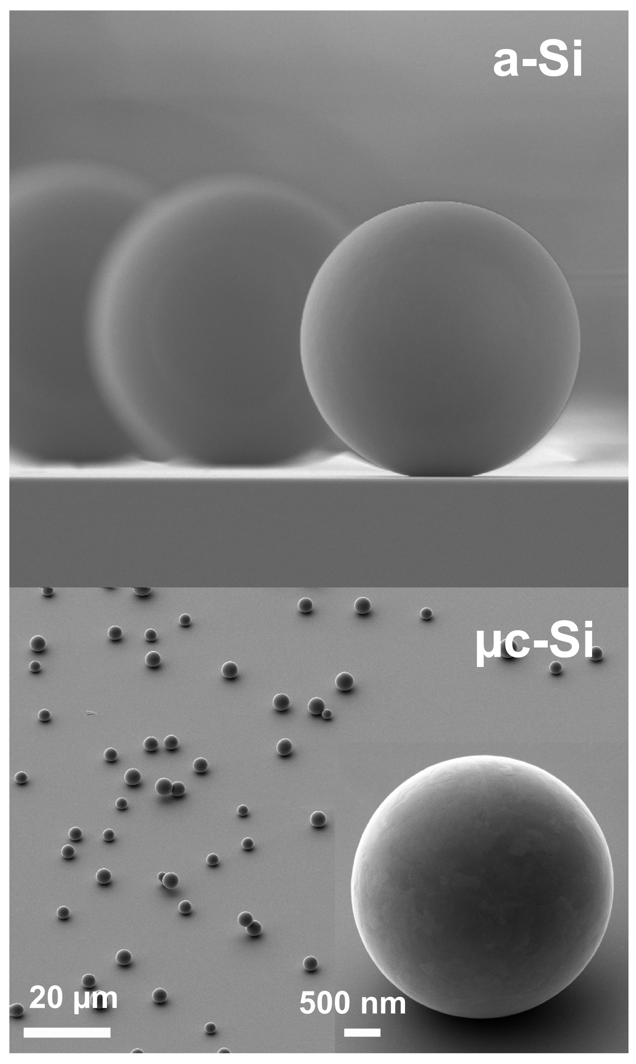
1. Synthesis of Si microspheres

Chemical Vapor Deposition (CVD):

Silicon microspheres are produced by hot-wall chemical vapour deposition (CVD) of disilane gas (Si_2H_6) in a closed reactor.

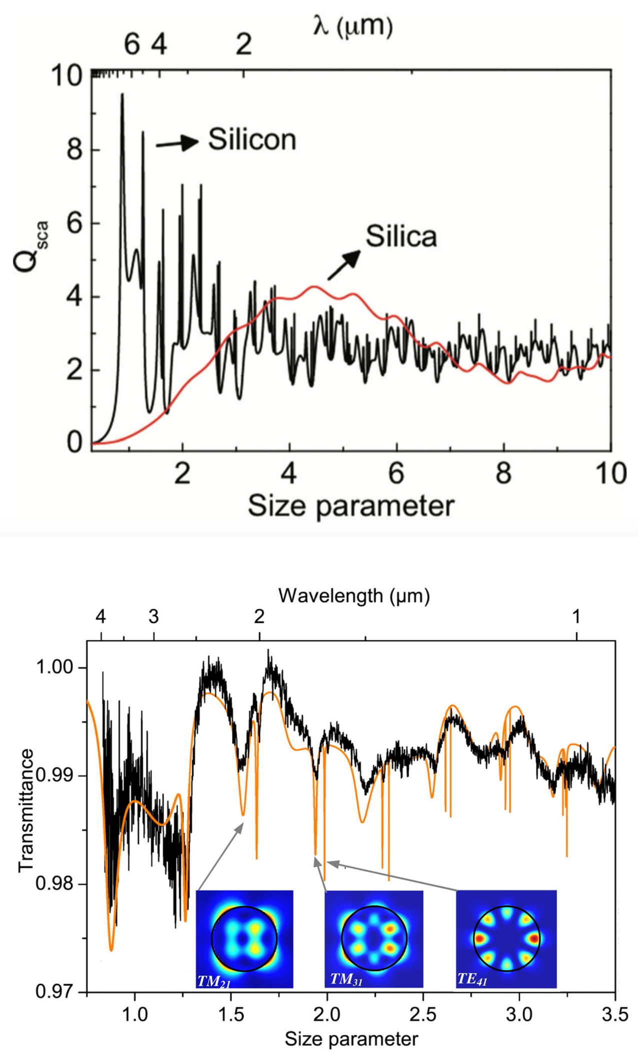
$$\mathrm{Si_2H_6}\ (g) \leftrightarrow 2\mathrm{Si}\ (s) + 3\mathrm{H_2}\ (g)$$

- **Amorphous spheres** obtained at low synthesis temperatures (T<600).
- **Microcrystalline spheres** obtained at high temperatures (T>600) or by further annealing amorphous particles.
- **Porous spheres** through frustrated process.
- **Polydisperse size** typ. 1–4 µm
- Isolated or aggregated (sponge-like)



after M. Garín *et al.* Nature Communications. **5**, 3440 (2014)

2. Mie Resonances



Silicon has a high refractive index.

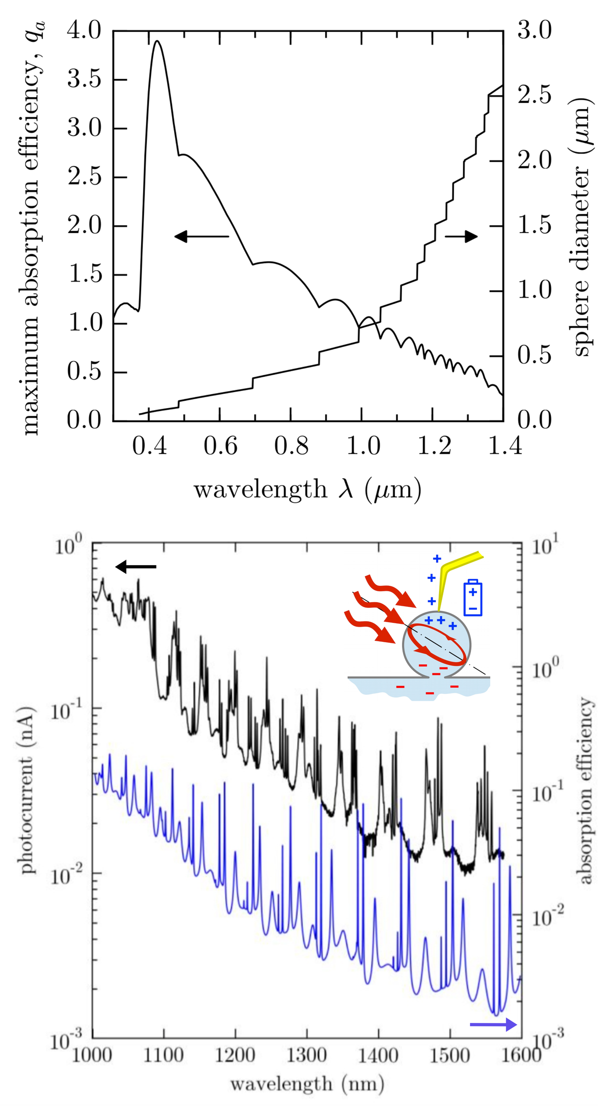
This leads to a rich scattering spectra with plenty of high-Q peaks, as compared to low-refractive-index microspheres such as silica.

Also, it exhibits very high scattering efficiencies, specially for the lowest order mode that reach values of around 10.

The transmission spectrum of a single microsphere over a silica substrate matches nicely the Mie spectrum

Figures after: F. Meseguer *et al.* J. Appl. Pys. **109** 102424 (2011)

3. Absorption by microspheres



Mie modes absorb the most when critically coupled:

$$k_{max} = \frac{n}{4Q} \Rightarrow q_a \approx \frac{q_s'}{4}$$

In the visible: *k* can be tuned by selecting the particle size.

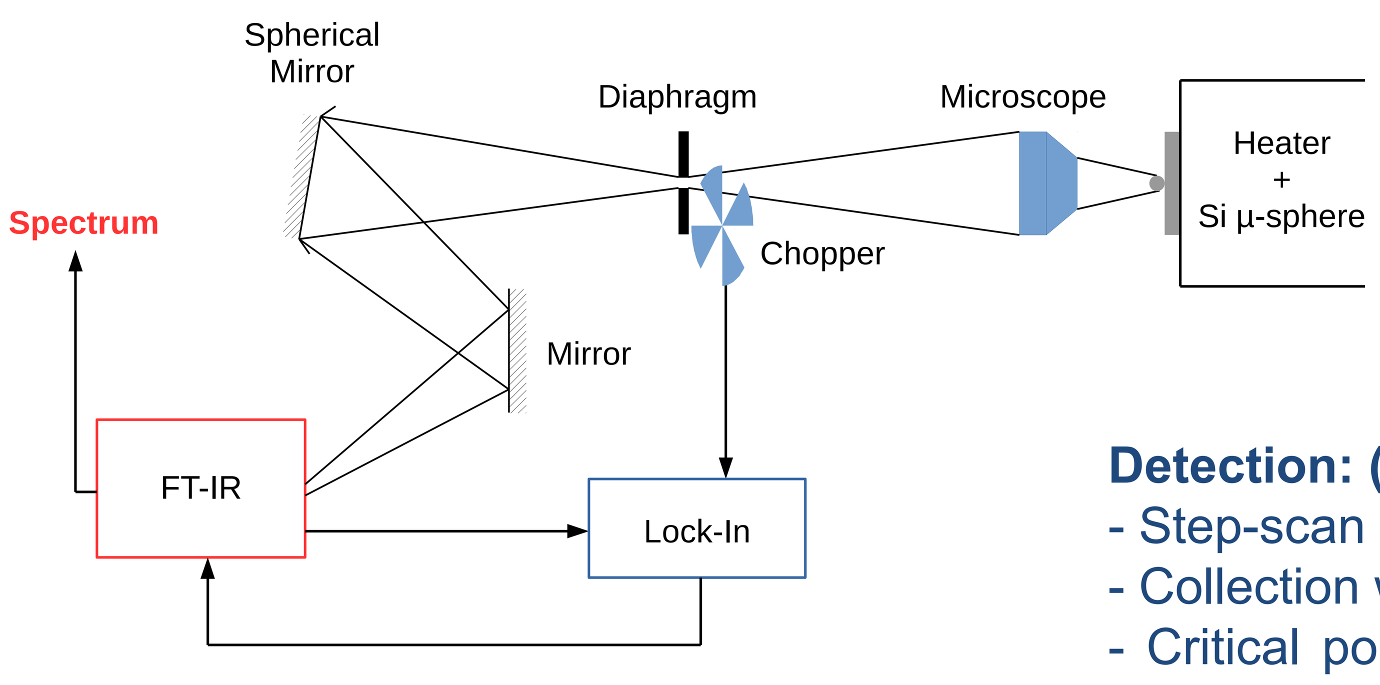
Fundamental modes (low-Q) excel at short wavelengths, where k is higher. → **Absorption efficiencies much higher than one.**

High-*Q* modes work better at long wavelengths, where silicon absorption is weak. Photons dwell in the cavity for very long times until absorbed, **even at the bandgap edge.**

In the NIR/MIR: *k* can be tuned by doping/contaminating

Figures after: M.Garín *et al.* J. Appl. Pys. **119** 033101 (2016) ; M. Garín *et al.* Nature Communications **5**, 3440 (2014)

4. Thermal Emission in the Mid-IR



- $q_e = q_a \rightarrow q_e > 1$
- Si has a weak absorption in the IR; increasing *k* is necessary for reaching good resonant absorption, for instance by doping.
- Idea: reach $q_e>1$ in the atmospheric window (wavelength range).

Detection: (set-up in progress).
- Step-scan FTIR in lock-in for improved sensitivity.
- Collection with Cassegrain objective.
- Critical points: radiometric calibration and precise particle temperature.

Summary

- Synthesis of Si microspheres by CVD
- Typ. diameter 1–4 µm
- Amorphous, microcrystalline and micro-porous silicon spheres.
- Strong and high-Q Mie resonances.
- Enhanced absorption with $q_{abs} > 1$
- Objective: use doped spheres for enhanced emissivity in the IR.
- In progress: measurement with step-scan FTIR and lock-in amplifier.

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