Heat Transfer in Dielectric Mirrors

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   - Heat transport
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   - Silicon multilayers reach less temperatures under solar concentration
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Perfect mirrors

The dielectric mirrors are called perfect mirror because of their high reflectivity. Multilayers of alternating periodic refraction index conform the structure of these mirrors[1].

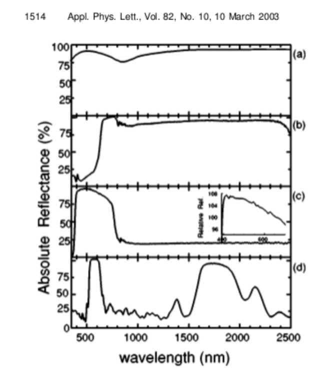

Figure: Reflectance of different porous silicon multilayers

[1] Agarwal, del Río. Appl. Phys. Lett. 82, 1512 (2003).

Perfect mirrors

If these structures are fabricated with ideal materials we obtain ideal mirrors or filters[2].

Figure: Good quality filters

[2] Agarwal, del Río. Appl. Phys. Lett. 82, 1512 (2003).

Perfect mirrors

We have fabricated mirrors. filters and photonic structures[3].

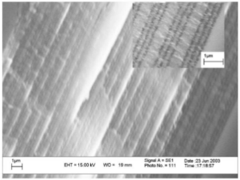

FIG. 1. Cross-sectional SEM image of the 20-cavity sample. The inset shows the amplified view of the structure.

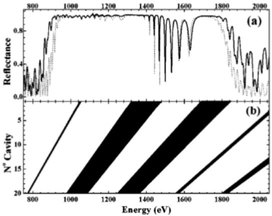

FIG. 2. (a) Solid line: Reflectivity of the 20-cavity sample measured at the incidence angle of 6°. The spectra above and below 1100 meV have been recorded with two different detectors. The dashed line shows the calculated reflectivity of this sample. (b) Band structure of the 20-cavity sample calculated by Eq. (5). White areas represent the allowed minibands and black areas represent the minigaps.

Figure: Good optical quality allows to find photonic Bloch oscillations

[3] Agarwal et al. Phys. Rev. Lett. 92, 097401 (2004).

Fabrication of porous silicon multilayers

Porous silicon is produced using electrochemical etching of crystalline silicon in a HF and glycerol solution in a volume ratio of 7 : 3 : 1.

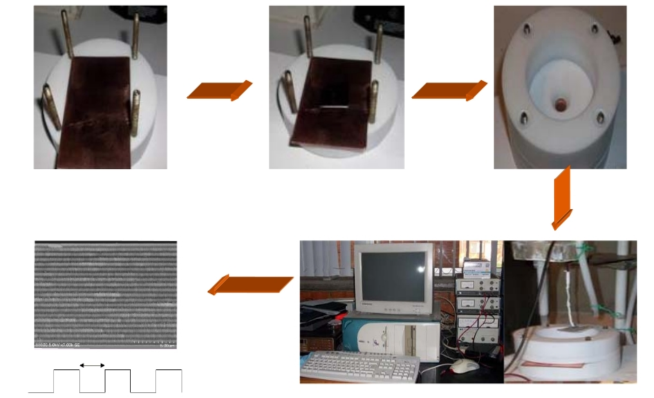

Figure: Fabrication steps

Porous silicon multilayers

Anodization with alternating current density between $1.5 - 40mA/cm^2$, layers of high and low porosity, 56% y 15% [4], and refractive indexes 1.4 and 2.4. We have 20 submirrors of 5 periods each, with a total width of $68.8\mu m$.

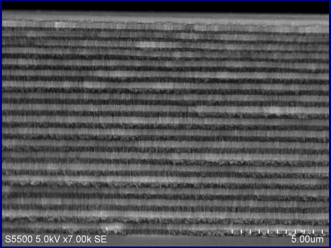

Figure: SEM image of transversal section of a p-Si multilayer

[4] Nava et al. Phys. Status Solidi C, 6, 1721 (2009)

Porous silicon multilayers

The structure of a p-Si multilayer is composed by a continuous arrangement of submirrors. Each mirror is designed to reflect a different wavelength λ and is formed by 20 periods. Values for λ are chosen as follows.

First the initial value λ_1 is given, the other values will follow the relation[5]: $\lambda_{i+1} - \lambda_i = 2 + i$ where i represents the number of submirrors. By designing multilayers with this properties we are able to fabricate mirrors which reflect in a continuous range of the spectrum.

[5] Agarwal and del Río Int. J. Modern Phys. B 10, 99 (2006).

Heat Transport in porous silicon mirror

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad 0 < r < R; \quad 0 < z < Z; t > 0,$$

with the following boundary conditions [6]

$$\frac{\partial T}{\partial r} = 0 \quad at \quad r \leqq R; 0 \leqq z \leqq Z \qquad (1)$$

$$-\kappa \frac{\partial T}{\partial r} = (1 - P_{Si})q_s + \varepsilon\sigma(T^4 - T_{amb}^4)$$

$$- \; h(T - T_{amb}) \quad at z = 0 \qquad 0 < r < R \qquad (2)$$

$$\frac{\partial T}{\partial z} = U(T - T_{amb}) \quad at \quad z = Z \quad 0 \leqq r \leqq R \qquad (3)$$

$$T = T_{amb} \quad at \quad t = 0 \qquad (4)$$

[6] de la Mora et al. Solar Energy Materials and Solar Cells 93 1218 (2009).

Effective thermal properties of porous silicon multilayers

Thermodynamic properties

1. We need to model the thermal conductivity and thermal diffusivity of each p-Si layer.
2. We need to model the effective heat transport coefficients.

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1. By use of averaging methods we determine those properties

Effective conductivity

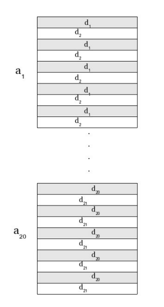

Figure: Scheme of the structure of submirrors in the multilayer, where a_i is the width of each one.

A submirror or p-Si is formed by $\frac{n}{2}$ periods of different porosities and lengths d_1 and d_2 respectively.

Effective conductivity in porous silicon multilayers

Heat transfer in porous materials can be calculated using effective media methods. We use a formula base on Reciprocity Theorem and Padê Approximant for a two component material[7]

$$\kappa_{eff} = \kappa_1 \frac{1 + c(\sqrt{\frac{\kappa_2}{\kappa_1}} - 1)}{1 + c(\sqrt{\frac{\kappa_1}{\kappa_2}} - 1)} \quad (5)$$

$\kappa_1 = 148 \frac{W}{K \cdot m}$ is the thermal conductivity of silicon and $\kappa_2 = 0.024 \frac{W}{K \cdot m}$ of air. This formula obeys Hashim-Strikman bounds.

[7] del Río, et al. Solid State Comm. 106, 183 (1998).

Effective conductivity in porous silicon multilayers

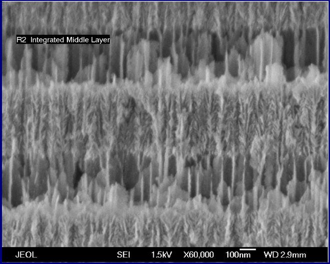

Figure: Nanoestructured porous silicon multilayer

For our periodic structure of layers of high (56%) and low (15%) porosity, κ_{eff} for each one was calculated, obtaining values of $\kappa_{eff_1} = 1.489\frac{W}{K \cdot m}$ and $\kappa_{eff_2} = 9.972\frac{W}{K \cdot m}$, respectively. We used these values to find effective thermal properties of p-Si multilayer.

Effective conductivity

Effective conductivity of the multilayer with 20 submirrors, each one with 5 periods,

$$k_1 = \frac{1}{d_1 + d_2} \sum_{i=1}^{\frac{n}{2}} (k_1 d_{1i} + k_2 d_{2i}), \tag{6}$$

where k_1 is the effective conductivity in the first layer and k_2 in the second, $a_i = d_{1i} + d_{2i}$. Then total effective conductivity of the multilayer, the next relation is used:

$$K_{eff_m} = \frac{k_1 a_1 + k_2 a_2 + \cdots + k_{20} a_{20}}{a_1 + a_2 + \cdots + a_{20}}, \tag{7}$$

where a_i is the width and k_i is the effective conductivity of each submirror, $i = 1, 2, \ldots, 20$.

Effective conductivity

Table: Values for effective thermal conductivity, effective specific heat and effective thermal diffusivity of the samples.

Sample	κ_{eff} $(\frac{W}{K \cdot m})$	$\rho c_{p_{eff}}$ $(\frac{J}{K \cdot m^3})$	α_{eff} $(\frac{m^2}{s})$
freestanding p-Si multilayer	3.18	68' 539.71	4.64×10^{-5}
p-Si multilayer + c-Si	138.67	1'530'382.30	9.06×10^{-5}
crystalline silicon	148.0	1'631'000.0	9.07×10^{-5}
aluminum mirror	0.914	2'074'359.24	4.40×10^{-7}
aluminized silicon	148.06	1'631'821.02	9.07×10^{-5}

Optical properties of p-Si mirrors

Our mirror was designed to reflect light from the visible to the near infrared (500 -2500 nm). To measure the reflectance of the samples a spectrophotometer UV-Vis-IR (Shimadzu UV1601) was used.

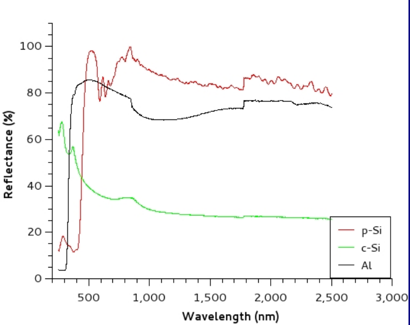

Figure: Reflectance spectrum of p-Si, c-Si and Al mirror

Experimental set up 1

Figure: Concentrating solar radiation on a porous silicon mirror

Varying the number of optical class parabolic mirrors focused on porous silicon mirror with and without cooling. Temperature was measured with a thermocouple.

Experimental set up 2

Figure: Experimental set up, heating three mirrors simultaneously

To study heat propagation in a p-Si mirror, a silicon wafer, and an aluminum mirror. The Al mirror is made of a very thin layer of aluminum (1.5 μm) covered with a glass of 3mm width. The c-Si wafer and p-Si mirror have both the same width of 1mm. We exposed them simultaneously under concentrated solar radiation and studied temperature change in each one of them.

Experimental set up 2

IR images were taken during the heating of the mirrors indicating a significant temperature increase. The temperature was measured in two different ways:

- Selecting the central spot of each sample and defining the temperature at the same point in all the images of the experimental series.
- Selecting an area (circle) that includes each mirror and estimating the average temperatures of the mirrors on each image sequence.

Thermocouple results

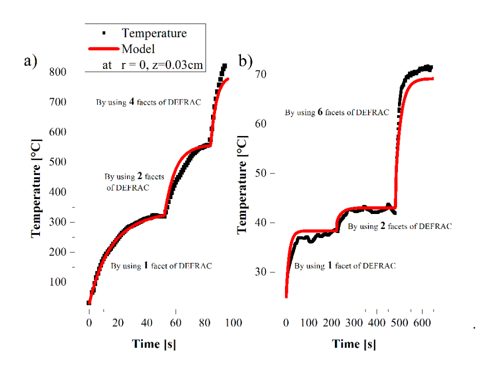

Figure: Time evolution of temperature a) without cooling, b) with cooling

Good agreement with modeling [8]. However the mirrors break.

[8] de la Mora et al. Solar Energy Materials and Solar Cells 93 1218 (2009).

Thermocouple results

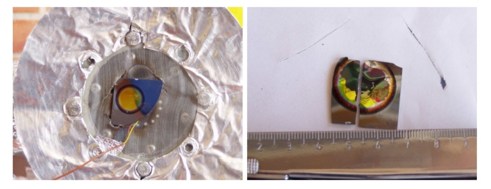

Figure: Porous silicon mirror before and after radiation without cooling

It seems that dilation plays a crucial role, but we need to understand whit more detail the heat transport [9]

[9] de la Mora et al. Solar Energy Materials and Solar Cells 93 1218 (2009).

Results

IR images were taken to measure temperature changes in the mirror after 3-5 min of exposure to concentrated solar radiation.

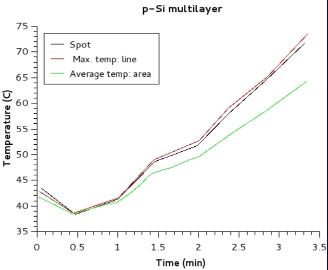

Figure: Temperature measurement vs. time in porous silicon mirror

Temperature increases of 30°C over environment temperature, reaching a final temperature of 70°C.

Comparison

IR images of the initial, intermediate and final measurements of the experimental session. The mirrors are top porous silicon, middle crystalline silicon and at bottom the aluminum mirror.

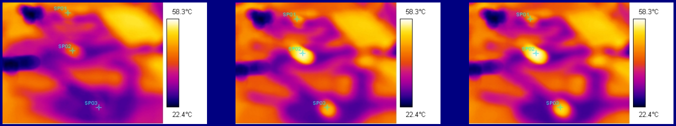

Figure: IR Image at time a) t= 0 min, b) t= 2 min, c) t= 4 min

Spot and area average comparisons

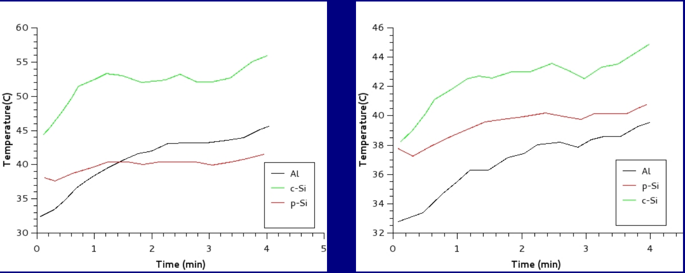

Figure: a) Temperature vs. time in spot b)Area average temperature vs. time of three mirrors

Comments

- Main problem with thermographic camera was the good quality of the porous silicon mirrors. We needed to pay attention to the reflection from sky.
- Even that we found that

$$\alpha_{eff_{Almirror}} < \alpha_{eff_{p-Si}} < \alpha_{eff_{c-Si}}.$$

  the porous silicon mirror shows interesting properties, because the increase on the temperature is less than on the other mirrors for the case of spot measurement.
- In the case of area average the role of the mass in the aluminum mirror is crucial to explain the difference.

Remarks

- We studied heat transfer in different dielectric mirrors.
- We designed and fabricated a porous silicon multilayer mirror and compared it to a silicon wafer, and a standard aluminum mirror.
- We show multilevel average method to calculate effective thermal properties for porous silicon multilayers.
- More detailed studies are needed to understand the heat transport in multilayers systems.
- Dielectric mirrors could be used as secondary mirrors in solar concentration systems.

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- More detailed studies are needed to understand the heat transport in multilayers systems.
- Dielectric mirrors could be used as secondary mirrors in solar concentration systems.
- We need to meassure temperature in small systems

Thanks!