Annual Report 2005, December 2005

Project
Colored Solar Collectors
Capteurs Solaires en Couleur

author and coauthors	Dr. Andreas Schüler, Estelle De Chambrier, Christian Roecker, Prof. Dr. Jean-Louis Scartezzini
institution	Ecole Polytechnique de Lausanne EPFL Laboratoire d'Energie Solaire et de Physique du Bâtiment LESO-PB
address	Bâtiment LE, 1015 Lausanne
phone, email,	(021) 693 4544, andreas.schueler@epfl.ch
webpage	http://lesowww.epfl.ch
SFOE Project-No.	43971
duration of project	Phase II: 01/02/2004 - 15/12/2006

SUMMARY

The architectural integration of thermal solar collectors into buildings is often limited by their black color, and the visibility of tubes and corrugations of the absorber sheets. A certain freedom in color choice would be desirable, but the colored appearance should not cause excessive performance degradation. Multilayered thin film interference filters on the collector glazing can produce a colored reflection, hiding the corrugated metal sheet, while transmitting the non-reflected radiation entirely to the absorber. These interference filters are designed and optimized by numerical simulation and shall be manufactured by the sol-gel dip-coating process. The proposed colored glazed solar collectors will be ideally suited for architectural integration into buildings, e.g. as solar active glass facades.

The availability of thin film materials with a refractive index lower than that of silicon favors a higher solar transmission at a given value of visible reflectance. The feasibility of the sol-gel deposition of such low refractive index materials has been demonstrated. For the development of nanostructured materials, analytical methods such as electron microscopy are extremely helpful. Important techniques of substrate pretreatment, sample cleaving, polishing, mounting, and microscope handling have been acquired. First measurements yield images of nanostructures produced by the sol-gel dip-coating process. Nanocomposite $Ti_xSi_{1-x}O_2$ thin films provide a large range of refractive indices. Aiming a high efficiency of the colored reflection, $Ti_xSi_{1-x}O_2$ based multilayered coatings have been designed and subsequently prepared by sol-gel dip-coating. The energy efficiency $M = R_{VIS}/(100\%-T_{sol})$ of the obtained colored reflection amounts up to 2.4. For a convincing demonstration sufficiently large samples of high quality are imperatively needed. An infrastructure for the handling of A4 sized samples has been established regarding substrate cleaning, multiple dip-coating and dust protected thermal annealing. All aspects of the cyclic process for multilayer deposition has been optimized yielding **homogenous coatings free of visible defects on a size scale suitable for demonstration (A4)**. One of the main technical risks of the project is now under control.

Project Goals

Architectural integration of solar energy systems into buildings has become a widely recognized issue, which regards techniques ranging from photovoltaics and daylighting to thermal solar energy conversion. Thermal solar collectors, typically equipped with black, optical selective absorber sheets, exhibit in general good energy conversion efficiencies. However, the black color, and sometimes the visibility of tubes and unwanted undulations of the thin metal sheets, limits the architectural integration into buildings. A recent opinion poll [1] showed that 85% of architects would prefer other colors than black, even if a lower efficiency was the price to pay.

Several research groups have proposed to color the absorber sheets. This can be obtained by modifying the process parameters used for the production of black selective absorber coatings. An alternative approach is to establish a colored reflection not from the absorber but from the collector glazing [2,3]. Interference colors of dielectric thin films are ideally suited for this purpose. Multilayered interference filters on the cover glass can produce an energy-efficient colored reflection, hiding the corrugated metal sheet, while transmitting the non-reflected radiation entirely to the absorber. These interference filters are designed and optimized by numerical simulation, and shall be manufactured by the sol-gel dip-coating process. Sol-gel dip coating does not require expensive vacuum equipment, and is already in use for the industrial production of anti-reflection coatings.

Goals for 2005 :

1. **Advanced thin film materials with low refractive index**

   The availability of thin film materials with a refractive index lower than that of silicon would favor a higher solar transmission at a given value of visible reflectance (see simulations in [3])

   The feasibility of the sol-gel deposition of the following materials shall be studied:

   - porous SiO_2
   - MgF_2
   - fluoride/oxide nanocomposite thin films

2. **Analytical techniques**

   For the development of nanostructured materials, analytical techniques such as electron microscopy are extremely helpful. The techniques of sample preparation and microscope handling shall be acquired, including

   - **pretreatment** for improving the wettability of silicon **substrates**
   - after thin film deposition: sample **cleaving**, **polishing** and **mounting**
   - synthesis of a **model system** suitable for optimizing instrument **resolution**
   - hands-on training on electron microscopes and **first measurements**

3. Multilayers of mixed oxides

Nanocomposite $\mathbf{Ti_xSi_{1-x}O_2}$ thin films provide a large range of refractive indices. Multilayered coatings with a **high efficiency** of the colored reflection shall be designed and prepared by sol-gel dip-coating.

4. Deposition of multilayers on large substrates (size A4)

For a convincing **demonstration** sufficiently large samples of high quality are imperatively needed. First colored multilayers on A4 sized glass substrates shall be manufactured in the laboratory, requiring:

- an **infrastructure** for **sample handling**
- an optimization of the **cyclic process for multilayer deposition**

Activities and Results

1. Advanced thin film materials with low refractive index

Simulations [3] have shown that the availability of low refractive index materials favors a higher solar transmission for the same value of visible reflectance. Among common sol-gel materials (mostly oxides, formed during annealing in air), silicon dioxide exhibits the lowest refractive index. Two approaches are considered for the synthesis of materials with a lower refractive index: the introduction of pores into silicon dioxide or the deposition of fluoride-based thin films.

1.1 Porous silicon dioxide

One way to decrease the refractive index of silicon dioxide is to introduce voids into the coating structure. However, in vacuum deposition processes the formation of pores is difficult to control. By adding organic macromolecules to sol-gel precursor solutions, xerogel films can be created which contain nanometric organic regions. In the subsequent annealing step, the organic macromolecules can be oxidized, thereby leaving behind nanometric pores.

As a macromolecule, polyethylene glycol PEG was chosen and added to the precursor solutions. Highly transparent porous SiO_2 films have been produced during the tempering step. Fig. 1 illustrates the evolution of normal transmittance spectra during pore formation (spectra as deposited and after one annealing step at 200°C, 350°C, 450°C and 550°C, respectively). After the heat treatment at 550°C the spectral transmittance at wavelengths around 550nm surpasses 98.5%.

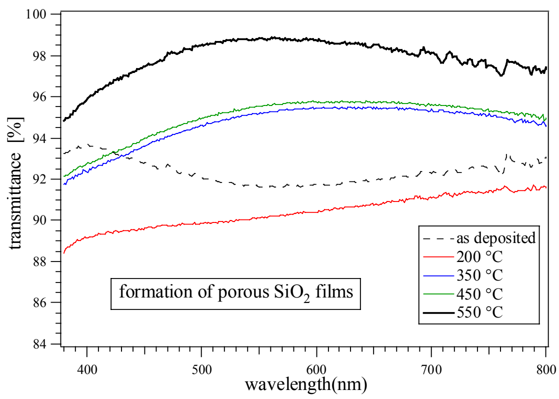


Fig.1: Evolution of normal transmittance spectra during pore formation (spectra as deposited and after one annealing step at 200°C, 350°C, 450°C and 550°C, respectively). After tempering at 550°C the spectral transmittance at wavelengths around 550nm surpasses 98.5%.

1.2 Magnesium fluoride MgF_2

The long-term optical performance of porous thin films might be degraded by hydrocarbons filling up the voids. An alternative approach to low-index materials is provided by fluorides such as MgF_2, which are compact materials but in general softer than SiO_2. In the annealing step following the deposition of the xerogel layers, the thin films are commonly exposed to air and thus harden and oxidize at the same time. Tempering in a nitrogen atmosphere, which would preserve the fluorides from oxidizing, can be envisaged but would mean an additional cost-rising effort. A common precursor for the sol-gel synthesis of MgF_2 is hydrofluoric acid HF. Due to its extreme chemical violence (HF attacks even glass) its use should be avoided.

A much less violent precursor, trifluoroacetic acid (TFA) has been used for the production of pure magnesium fluoride films. The wettability of the used solutions appeared to be somewhat critical and not always satisfying. MgF_2 films have finally been obtained as well by annealing in nitrogen atmosphere as in ambient air. For the annealing in nitrogen, a special bakeout reactor was used, but it turned out that MgF_2 films could also be formed as well by normal tempering in air. Fig. 2 illustrates the dispersion relation n(λ) of sol-gel deposited MgF_2 films. A dependence of the refractive index on the annealing temperature is observed, rising the question whether at 400°C a small volume fraction of pores is formed. Due to the observed wettability problems and haze formation during annealing, the quality of the deposited thin films is rather moderate as compared to the titanium silicon oxide films.

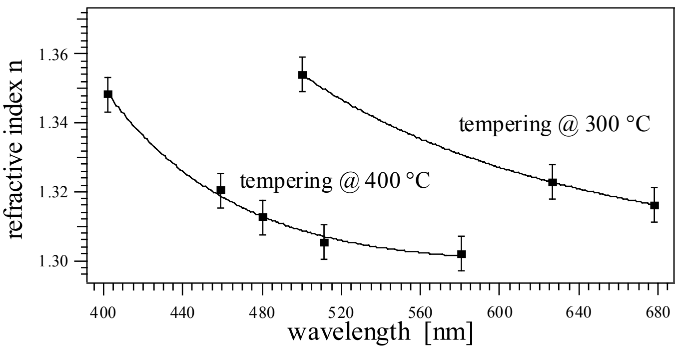


Fig.2: Dispersion relation n(λ) of sol-gel deposited MgF_2 films. A dependence of the refractive index on the annealing temperature is observed, rising the question whether at 400°C a small volume fraction of pores is formed.

1.3 Fluoride/oxide nanocomposite thin films

Magnesium fluoride MgF_2 is one of the rare thin film materials in use exhibiting a refractive index lower than that of SiO_2. Its application though is restricted by its lower hardness and eventually occurring adhesion problems. Aiming at superior film properties and at a tunable refractive index, a novel nanocomposite material has been created by mixing fluorides and oxides.

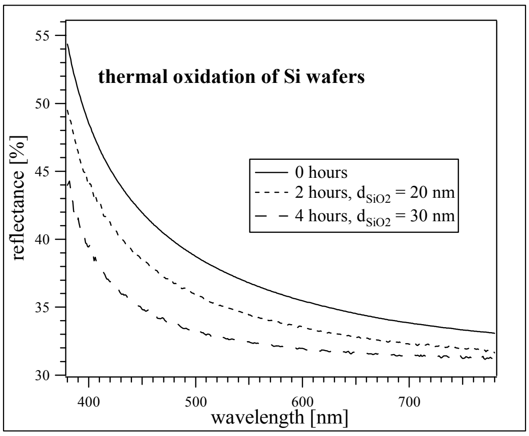
Precursor solutions have been developed which are compatible with each other when mixing them after separate hydrolysis. Annealing can be performed simply in ambient air. Due to a better wettability, the dip-coating process turned out to be much less difficult than for the MgF_2 precursor solution. In addition, the tendency to form haze is much lower, yielding a considerably higher film quality. Refractive index values considerably lower than that of SiO_2 have been achieved. Details can be found in the SFOE report "Feasibility study on the sol-gel deposition of nanostructured materials based on oxides and fluorides for coatings on solar collector glazing", (Oct. 2005).

In order to understand the highly interesting optical properties of these films, further investigations of the morphology and nanostructure of such films are necessary.

2. Progress in analytical techniques

2.1 Pretreatment of silicon substrates

For certain powerful thin film analysis techniques such as electron microscopy and X-ray diffraction, the use of glass substrates is extremely difficult. It is preferable to work with a semiconducting, cristalline and cleavable substrate material such as silicon. However, in the sol-gel dip-coating process the wettability of certain solutions is much better for the normal glass substrates than for silicon substrates. By thermal oxidation of the silicon wafers at elevated temperature (850°C) the wettability could be significantly improved. Annealing during 4 hours at 850°C results in the formation of a 30 nm thick SiO_2 layer as inferred by optical measurements (see Fig. 3a). A closed film can be deposited on the likewise pretreated substrate by dip-coating, without any loss of wettability (see Fig. 3b).

a)


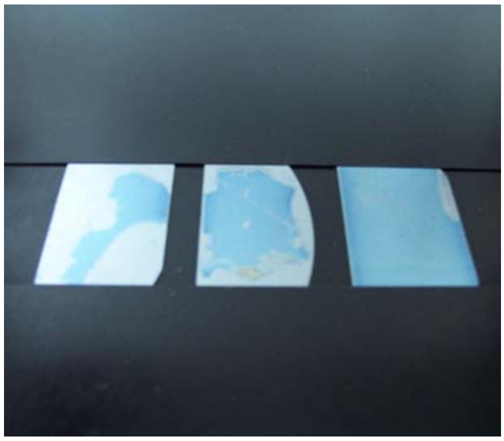
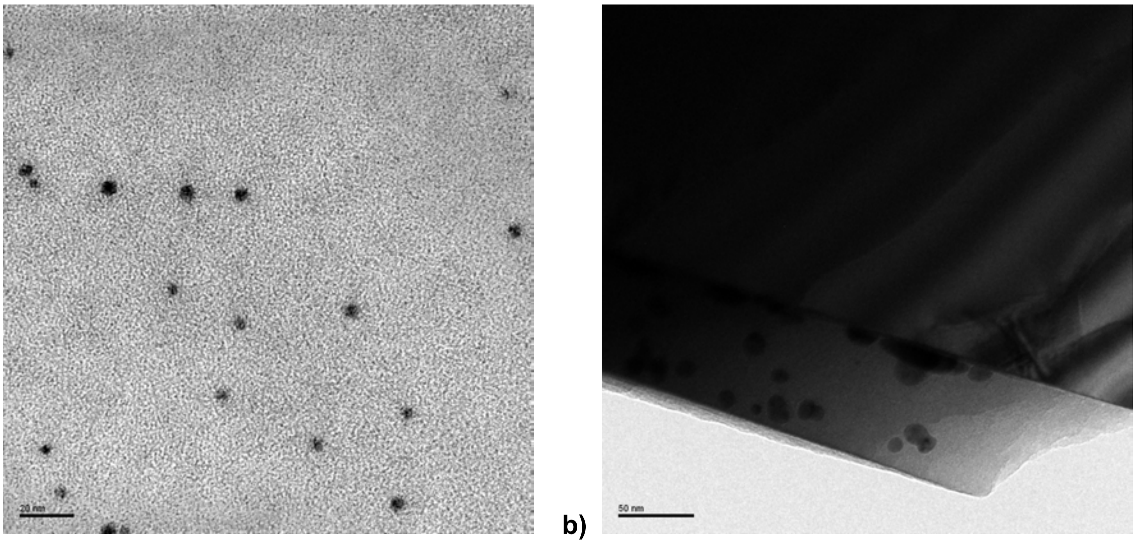
b)


Fig.3: Pretreatment of Si wafers by thermal oxidation at 850°C. a) Normal reflectance spectra obtained from the substrate as received, and after thermal annealing during 2 and 4 hours. A silicon dioxide layer is formed, with a thickness of 20 nm and 30 nm respectively. b) Result of dip-coating using a precursor solution for porous SiO_2. From left to right: substrate as received, after thermal annealing during 2 and during 4 hours. The formation of 30 nm of silicon dioxide improves the wettability clearly, yielding the formation of a closed film.

2.2 Imaging of sol-gel made nanostructures by transmission electron microscopy TEM

Transmission electron microscopy is a powerful tool for the investigation of nanostructures of thin films. A model system with sufficiently small structures and high contrast for electrons is desired for testing and optimizing the technique. SiO_2 films containing nanometric gold clusters should therefore be perfectly suited for the considered purpose. The precipitation of nanometer-sized gold aggregates has been achieved by adding $AuCl_4$ to the precursor solution. The gold nanocrystals have been resolved by transmission electron microscopy, confirming that nanostructures can be produced on large areas by simple sol-gel dip coating. Fig. 4a) shows a view of a thin film deposited on a coated copper TEM grid (viewing axis perpendicular to thin film plane). Fig. 4b) shows a side-view of a cleaved sample (thin film on silicon 100 substrate, viewing axis in film plane). The fringes observed in the region of the Si substrate are due to electron interference.



a) b)

Fig.4: a) Image by transmission electron microscopy of a thin SiO_2:Au film deposited on a coated copper TEM grid. The viewing axis is perpendicular to thin film plane. Gold nanoparticles can clearly be resolved. b) TEM side-view of a cleaved sample. The 75 nm thin SiO_2:Au film was deposited on a silicon 100 substrate. The viewing axis is in the film plane.

3. Multilayers of mixed oxides

By mixing silicon oxide ($n \approx 1.47$) and titanium oxide (for thin films $n \approx 2.2$) any intermediate refractive index can be achieved, opening manifold possibilities for multilayer design.

Multilayered interference stacks of up to six layers were produced by alternating dip-coating and tempering steps. Previous computer simulations [3] indicated favorable multilayer designs regarding refractive indices and thickness of the stacked layers. We chose SiO_2 and $Ti_{O.5}Si_{0.5}O_2$ as low and high index materials respectively, and thin film designs which are very close to quarterwave stacks, with the position of the reflectance peak at 535 nm.

The multilayer formation during repeated dip-coating and tempering has been monitored by acquiring transmittance spectra after each annealing step, yielding information on the thickness of each individual layer added. The experimental reflectance curve obtained from such a multilayered sample is shown in Fig.5. A distinct reflectance peak is observed at 535 nm, with a full width at half maximum of approx. 180 nm. The transmittance spectrum exhibits a complementary dip at 535 nm and spectral regions of antireflection. The visible reflectance R_{VIS} and the CIE color coordinates x,y have been determined from the reflectance spectrum, yielding R_{VIS} = 61.4 %, x = 0.32 and y = 0.42. The solar transmission amounts to 75.4 %, the energy efficiency of the colored reflection $M = R_{VIS}/(100\%-T_{sol})$ to 2.4.

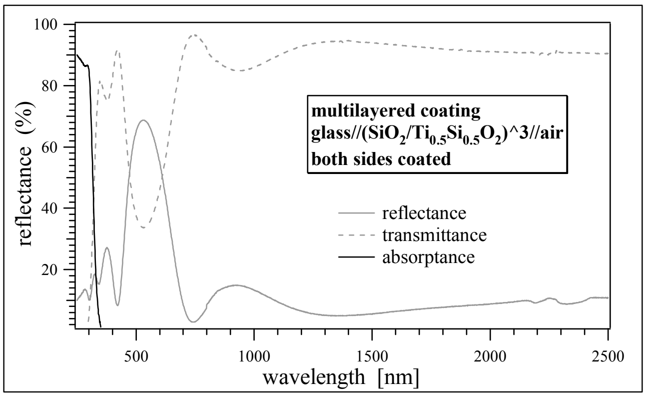


Fig.5: Experimental reflectance, transmittance, and absorptance spectra of a multilayered SiO_2 / $Ti_{0.5}Si_{0.5}O_2$ thin film stack on glass, after deposition of six layers. A distinct reflectance peak is observed at 535 nm. The visible reflectance R_{VIS} and the CIE color coordinates x,y have been determined from the reflectance spectrum, yielding R_{VIS} = 61.4 %, x = 0.32 and y = 0.42. The solar transmission amounts to 75.4 %, the energy efficiency of the colored reflection M = R_{VIS}/(100%-T_{sol}) to 2.4.

4. Deposition of multilayers on large substrates (size A4)

One of the main technical risks of the project is related to the fact that to provide convincing samples for demonstration it is absolutely necessary to have coatings of high quality. It shall be shown that colored multilayered coatings can be manufactured in a satisfying quality by the sol-gel dip-coating process. Important factors for the quality of the coatings are particle-free solutions, the vibration free movement during sample withdrawal from the solution, and the protection from dust during dip-coating and repeated thermal annealing.

4.1 Establishing the infrastructure for sample handling

Before coating, substrates have to be free of dust and grease. In order to ensure a high level of substrate cleaning, a professional laboratory dishwasher has been installed. Residual free cleaning by deionised water can thus be provided. A rack has been built for the A4 sized substrates, holding the glass panes during washing and drying.

Special reservoirs allow dip-coating of the A4 sized substrates. In order to keep the quantity of needed precursor solution low, the reservoirs are narrow but can be opened laterally for easy cleaning.

During the annealing step following the dip-coating procedure, the samples have to be protected from the particles present in the ambient laboratory air. A special bake-out container has been constructed, fitting ten samples of the A4 size (see Fig 6a). The recipient is charged in the particle-free atmosphere provided by the filtered laminar flow, closed and subsequently transferred to the oven. After annealing, the container is transferred back to the laminar flow chapel again, where a subsequent dip-coating step can take place. Dip-coater, sample rack and bake-out container just fit into the laminar flux chapel (see Fig. 6b).

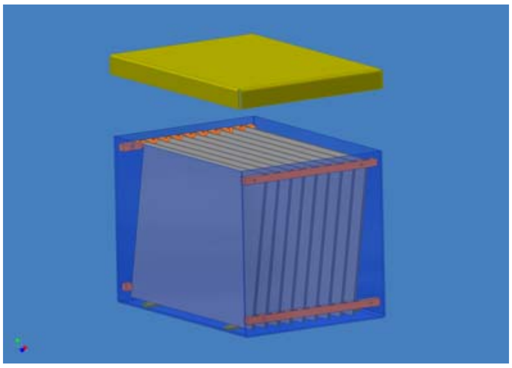
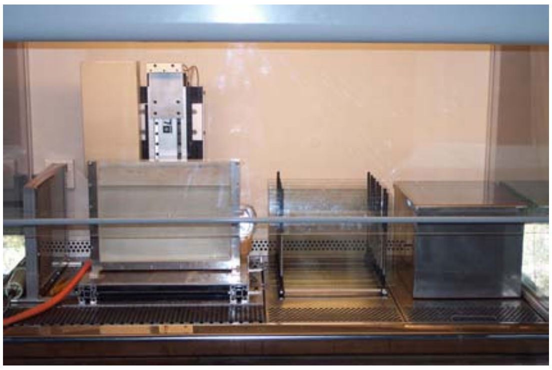
a)  b) 

Fig.6: a) Bake-out container for A4 sized samples. During the annealing step, samples remain under the protection from dust. b) Laminar flux chapel with dip-coater, sample rack and bake-out container (from left to right).

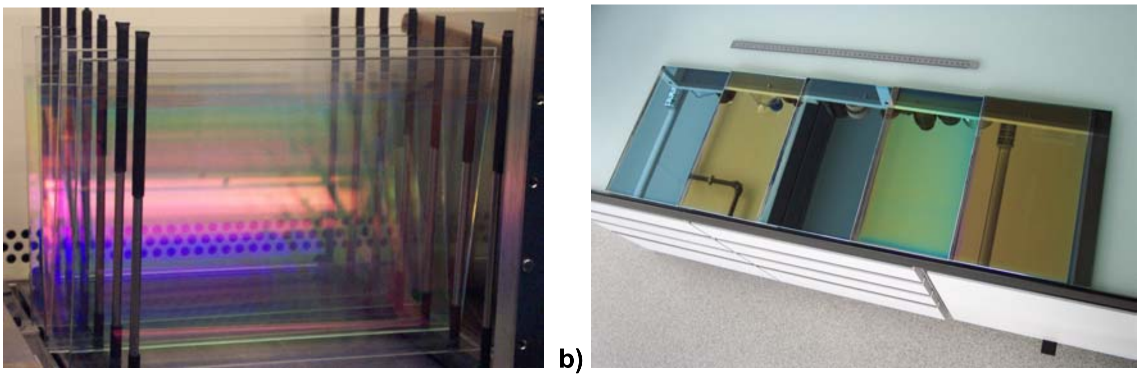
4.2 Elaborating the process for high quality multilayer deposition

The preparation of defect-free homogenous multilayers requires an optimization of all aspects of substrate pretreatment, sample processing and handling.

The complete process includes:

- substrate washing with detergent, neutralisation step and subsequent rinsing cycles with deionised water
- transfer to laminar flow chapel
- mounting of substrate, removal of dust particles by anti-static brush or filtered nitrogen jet
- dip-coating (interruption of laminar flow for homogenous solvent evaporation)
- dissolution of excess gel on bottom edge of sample
- transfer to oven in closed bake-out container
- transfer back to laminar flow chapel
- subsequent dip-coating/annealing steps for multilayer formation

Fig. 7a) shows the glass panes during sol-gel processing in the drying rack. The resulting colored multilayered coatings are free of visible defects and exhibit a good homogeneity (see Fig. 6b). Various shades of color have been obtained by varying the withdrawal speed.

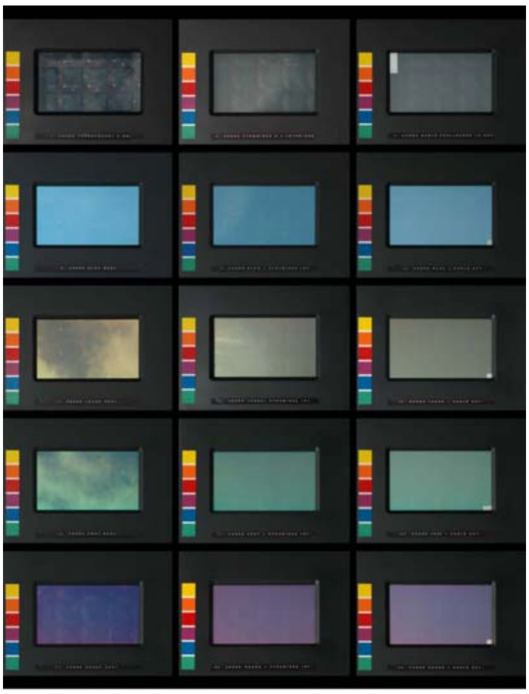


a) b)

Fig. 7: a) Glass panes during sol-gel processing. a) The resulting colored multilayered coatings are free of visible defects and exhibit a good homogeneity. Various color shades have been obtained by varying the withdrawal speed.

4.3 Demonstration

In order to visualize the design possibilities for colored solar facades, a collector model ("Demo-Box") has been build, which can be used to expose the A4 sized colored glazing samples with a real selective black absorber sheet behind. The colored glass panes can be combined with differently textured front glazing in order to study the effect of diffusing surfaces/interfaces. This Demo-Box has already proven to be very helpful in discussions with architects and facade manufacturers.



D E M O B O I T E – E P F L / L E S O P B

Fig. 8: Demonstration of various color shades and surface textures in combination with black selective absorber sheet behind the glazing. Top left: untreated solar glass for comparison.

Dissemination/industry contacts

- Presentation of the project and exhibition of the “Demo-Box” at the « Réunion annuelle de la section romande de la Centrale Suisse des constructeurs de fenêtres et façades CSFF » meeting with numerous participants from industry
- Interaction with CENTROSOLAR GLAS GmbH, Germany (former FLABEG), in order to prepare the proposal of a new European project COSOLFACE, aiming at the development of a solar façade system based on the new colored collector glazing

National Collaboration

A close collaboration exists with the research group of Prof. Peter Oelhafen, Institute of Physics, University of Basel. The optical measurements performed by Gregory de Temmerman and Dr. Teresa de los Arcos should specially be mentioned. The collaboration can be characterized as cooperative and productive.

International Collaboration

Current European project *SOLABS*,

partners from France, Spain, Slovenia, Germany and Switzerland. Even though the topics of glazed and unglazed thermal solar collectors are clearly separated, synergies emerge especially regarding architectural aspects.

Name of Project:

"Development of unglazed solar absorbers (resorting to coloured selective coatings in steel material) for building facades, and integration into heating systems"

EU project number: NNE5-2001-00963

Preparation of a new proposal to the European Union : project COSOLFACE,

partners from France, Germany, Greece, Sweden and Switzerland, including solar collector industry (CLIPSOL, France), and glass coating industry (CENTROSOLAR GLAS, Germany). The project aims at the development of a multifunctional solar facade based on the glazing developed in this project. The envisaged active solar thermal system will provide heat in winter and solar cooling in summer.

Collaboration with Polymer Competence Centre PCCL, University of Leoben, Austria,

theory and modelling of thin film optics, group Dr. Dieter Gruber

Evaluation 2005 and Outlook 2006

Major advances have been made in 2005 regarding the various aspects of the project: the range of accessible materials has been extended from compact oxides to porous materials, fluorides and fluoride/oxide nanocomposites. Electron microscopy has been established as a valuable tool for the direct imaging of the nanostructures. Multilayers of mixed oxides show high energy efficiencies of the colored reflection. A breakthrough has been achieved regarding the size and quality of the multilayered coatings: A4 sized substrates have been processed yielding first large samples of high quality suitable for a convincing demonstration of the idea.

Project goals accomplished in 2005 :

1. **Advanced thin film materials with low refractive index**

   The feasibility of the sol-gel deposition of the following low refractive index materials has been demonstrated:

   - porous SiO_2
   - MgF_2
   - fluoride/oxide nanocomposite thin films

2. **Analytical techniques**

   Important techniques of substrate pretreatment by thermal annealing, sample cleaving, polishing, mounting, and microscope handling have been acquired. A nanostructured model system (SiO_2:Au) suitable for optimizing the instrument resolution has been synthesized. First measurements yield images of nanostructures produced by the sol-gel dip-coating process.

3. **Multilayers of mixed oxides**

   Multilayered coatings with a high efficiency of the colored reflection have been designed and prepared by sol-gel dip-coating. The energy efficiency $M = R_{VIS}/(100\%-T_{sol})$ of the obtained colored reflection amounts up to 2.4.

4. **Deposition of first multilayers on large substrates (size A4)**

   An infrastructure for the handling of A4 sized samples has been established regarding substrate cleaning, multiple dip-coating and dust protected thermal annealing. All aspects of the cyclic process for multilayer deposition have been optimized yielding **homogenous coatings free of visible defects**.

Topics for 2006 :

- structural characterization of nanocomposite/nanoporous materials
- advanced materials on large scale (A4)
- feasibility of substituting the intermediate annealing steps by UV hardening

Publications 2005

Schüler A., Boudaden J., Oelhafen P., De Chambrier E., Roecker C., Scartezzini J.-L., ***Thin film multilayer design types for colored glazed thermal collectors***, Solar Energy Materials & Solar Cells ***89***, 219 (2005)

Oelhafen P., Schüler A., ***Nanostructured Materials for Solar Energy Conversion***, Solar Energy ***79***, 110 (2005)

Schüler A., Roecker C., Boudaden J., Oelhafen P., Scartezzini J.-L.**,** ***Potential of quarterwave interference stacks for colored thermal solar collectors***, Solar Energy ***79***, 122 (2005)

Schüler A., Dutta D., De Chambrier E., De Temmerman G., Oelhafen P., Roecker C., Scartezzini J.-L., ***Sol-gel deposition and optical characterization of multilayered silicon oxide//titanium silicon mixed oxide thin films on solar collector glasses,*** Proceedings of ISES World 2005 Conference, 6-13 August 2005, Orlando, USA

M.-C. Munari Probst, C. Roecker, A. Schüler, ***Architectural integration of solar thermal collectors: results of a European survey***, Proceedings of ISES World 2005 Conference, 6-13 August 2005, Orlando, USA

Schüler A., De Chambrier E., Dutta D., Roecjker C., Scartezzini J.-L., ***Angle-dependent spectrophotometry of sol-gel deposited multilayered oxide coatings on solar collector glasses,*** Proceedings of the CISBAT 2005 international conference Lausanne, 28-29 September 2005

Python M., De Chambrier E., Schüler A., ***Photoluminescence of quantum dots for solar energy applications***, Proceedings of the CISBAT 2005 international conference Lausanne, 28-29 September 2005

M.-C. Munari Probst, C. Roecker, ***Integration and formal development of solar thermal collectors***, proceedings of the PLEA conference, 497-502, Beirut, 13-16 Nov. 2005, ***best paper award***

Oral Presentations 2005

Schüler A., ***Nanotechnology for Solar Thermal Energy Conversion***, invited talk, Mai 2005, University of Leoben, Austria

Schüler A., ***Sol-gel deposition and optical characterization of multilayered silicon oxide // titanium silicon mixed oxide thin films on solar collector glasses***, ISES World 2005 Conference, Orlando, USA

Roecker C., ***Architectural integration of solar thermal collectors: results of a European survey***, Proceedings of ISES World 2005 Conference, 6-13 August 2005, Orlando, USA

Schüler A., ***Angle-dependent spectrophotometry of sol-gel deposited multilayered oxide coatings on solar collector glasses,*** CISBAT 2005 international conference Lausanne, 28-29 September 2005

Python M., ***Photoluminescence of quantum dots for solar energy applications***, CISBAT 2005 international conference Lausanne, 28-29 September 2005

De Chambrier E., " **Matériaux diélectriques nanostructurés pour vitrages colorés sur capteurs solaires thermiques",** Séminaire LESO-PB, EPFL, Oct. 2005

Roecker C., Schüler A., ***Développement de vitrages colorés pour façades solaires***, présentation à l'occasion de la réunion annuelle de la section romande de la Centrale Suisse des constructeurs de Fenêtres et Façades CSFF , Chateau de la Sarraz, Dec. 2005

Scartezzini J.-L., Schüler A., ***L'énergie solaire : une alternative durable a Katrina, Rita, Wilma ... et les autres***, lecture invited by the Service Intercommunal de l'Electricité SIE SA, Polydome EPFL, Nov. 2005

M.-C. Munari Probst, C. Roecker, ***Integration and Formal development of solar thermal collectors***, PLEA conference Beirut, 13-16 Nov. 2005

PhD work in progress

Estelle de Chambrier, Déposition du Plan de Thèse, ***Matériaux diélectriques nanostructurés pour vitrages colorés sur capteurs solaires thermiques***, Nov. 2005

Master's theses (related topics)

Remy Carera, Royal Institute of Technology, Stockholm, Sweden, ***Towards corrosion-resistant low emittance coatings for unglazed facade collectors***

Martin Python, EPFL, ***Fluorescence of quantum dots***

Visiting Students

Hitesh Chelawat, Indian Institute of Technology IIT Bombay, India

Deepanshu Dutta, Indian Institute of Technology IIT New Delhi, India

TEM training

by Prof. Philippe-André Buffat, Dr. Aïcha Hessler, Dr. Marco Cantoni, Danièle Laub, Fabienne Bobard, Centre Interdépartemental de la Microscopie Electronique CIME, EPFL

Architectural aspects

Maria-Cristina Munari Probst

Technical support

Pierre Loesch, LESO

References

[1] Weiss W., Stadler I., 2001. ***Facade Integration – a new and promising opportunity for thermal solar collectors.*** Proceedings of the Industry Workshop of the IEA Solar Heating and Cooling Programme, Task 26 in Delft, The Netherlands, April 2, 2001 (http://www.fys.uio.no/kjerne/task26/pdf/industry_workshop_delft.pdf)

[2] Schüler A., Roecker C., Scartezzini J.-L. (EPFL), Boudaden J., Videnovic I.R., Ho R.S.-C., Oelhafen P., ***On the feasibility of colored glazed thermal solar collectors based on thin film interference filters***, Solar Energy Materials & Solar Cells ***84***, 241 (2004)

[3] Schüler A., Roecker C., Scartezzini J.-L., Boudaden J., Oelhafen P., ***Designing thin film multilayers for colored glazed thermal collectors***, EUROSUN 2004 Proceedings, June 2004, Freiburg im Breisgau, Germany