Energy Efficient Coatings in The Nanohouse™ Initiative

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Abstract

The University of Technology, Sydney (UTS), in collaboration with CSIRO has created the Nanohouse™ initiative, a concept that serves as the conceptual framework for various pedagogical, scientific, architectural and engineering activities at the University. Housing is a significant item in both personal and regional budgets, and the Nanohouse™ therefore serves as a powerful vehicle for demonstrating nanotechnologies. One of the major energy-efficient components of the Nanohouse™ are nano-engineered coatings and films for transparent and translucent surfaces that modify their optical properties. These nanostructured materials can provide wavelength-selective control of reflection, absorption and transmission of light as well as angular selectivity for directional control, making it possible to design houses that have very large windows and skylights, but which nevertheless remain cool in summer and warm in winter. We have already made significant progress towards the development of these nanotechnologies. In this paper will be discuss the design and performance of these optically controllable nano-coatings and their application to the Nanohouse™.

PACS: 78.67.Bf; 81.05.Mh; 42.79.Wc

Keywords: Nanoparticles; NIR absorption; Solar control glazing; Optical coatings.

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1. Introduction

The Nanohouse™ Initiative is a collaboration between scientists, engineers, architects, designers and builders to design, and eventually build, the house of the future exploiting the potential of nanotechnology. At present, the Nanohouse™ exists in virtual form, as architectural drawings, mathematical models and as a 3D computer simulation. It is a pre-fabricated modular system that has been designed to incorporate the best and most appropriate nanotechnologies available. The current focus is to create a built environment that is environmentally friendly and allows comfortable and convenient living through climate control with nanoengineered window glazing systems. Naturally, the design and methodology will evolve over time as new materials and technologies are incorporated into the Nanohouse™ bringing new functionalities and benefits.

The potential benefits of solar control glazing are not insignificant given that around 30 % of heat transfer in and out of typical buildings is through windows and around 5% of all electricity produced is wasted by windows [1]. Furthermore, worldwide there are around 27 billion m^2 of architectural glass and an annual flat-glass production approaching 2 billion m^2 [2]. In cold climates the problem is to control heat transfer from interior to exterior by convection; multiple layer glazing systems provide an effective and commonly used solution. In tropical climates, it is solar radiation passing into the building and heating the interior that must be controlled. In this case the optical properties of the glass can be modified by some means to block the infra-red component of solar radiation, or near infra-red (NIR), and thereby reduce heating effects. Combinations of double glazing / NIR blocking will provide optimum solutions for sub-tropical and temperate regions with hot summers and cold winters. The present paper provides an overview of nanoengineered solar control glazing technologies and their relative merits.

2. Control of Optical Properties

In the context of energy efficient fenestration, the objective is to be able to engineer optical properties of window glass such that near infra-red wavelengths are blocked or reduced while visible wavelengths are relatively unaffected. In warmer climate zones this provides reduced energy consumption for cooling with improved external view performance. Two methods for achieving these ends are wavelength selectivity and angular selectivity.

The pertinent properties are then transmittance T, and reflectance R, as a function of wavelength and angle of incidence, and can be measured using a suitable spectrophotometer. Calculated parameters such as the total solar transmittance T_{sol}, and visible transmittance T_{vis} quantify optical performance [3]. These quantities are a measure of the amount of solar radiation transmitted across all solar wavelengths (300-2500nm) and amount transmitted across the visible wavelengths respectively. The aim is to reduce T_{sol} while maintaining T_{vis} by reducing NIR transmission while maintaining visibility. Care must be taken here, as IR absorbing materials, while blocking IR effectively, can still 'transmit' considerable heat through a window. Solar absorptance A_{sol}, and solar heat gain coefficient, SHCG, which takes re-emitted heat into account also become important parameters in this case.

2.1. Wavelength Selective Technologies

Single layer thin metallic coatings for glass have been available for some time. They show a transition from transmission to rising reflectance as a function of wavelength, with the transmission maximum and transition wavelength determined by intrinsic properties of the film, in particular the free electron density. However, they do not transmit neutral light, for example both Au [4] and TiN [5] thin films are gold coloured in reflection while transmitting greenish light. With TiN_x thin films it is possible to engineer the optical properties by changing the N/Ti ratio. Increasing this ratio decreases the free electron density and pushes the reflection edge to longer wavelengths. The challenge is to obtain a high enough ratio that reflection occurs in the near IR, while maintaining the metallic character of the film.

Multilayer thin films consisting of metallic layers sandwiched between high refractive index insulators, e.g TiO_2/Ag/TiO_2, provide very good optical performance [6]. The dielectric acts both as a protector and anti-reflection coating for the soft metallic layer. Again optical control is mainly by reflection, but unlike single layers, can be tuned by altering the layer thickness [7]. Performance can be chosen according to the degree of light gain and view needed, available combinations include T_{sol} = 46%, T_{vis} = 76%, and T_{sol} = 21%, T_{vis} = 56%. These complex multilayer coatings are, however expensive to apply despite the low cost of the raw materials used.

An alternative to reflective coatings is to use particle doped polymers that absorb solar radiation. With particles in the micron size regime scattering of the light occurs and the polymer is translucent. If the particles are made small enough and kept separated then the polymer becomes transparent. Particle size is determined by refractive index, and is typically in the nanoscale regime. To keep particles separated, concentrations of dopant particles must be kept low and care taken to disperse the particles adequately in the polymer matrix. By selecting nanoparticles with the appropriate absorptive properties the doped polymer can be engineered for spectrally selective control even at very low dopant concentrations. Nanoparticles embedded in a polymer can be particularly efficient absorbers. An absorption resonance occurs at a wavelength where the dielectric constant of the nanoparticle is negative and twice the dielectric constant of the host matrix. The position, width and strength of this resonance can be controlled by varying the free-electron density in the nanoparticles. Oxide conductors, and other materials with lower electron densities are ideal candidates as they absorb in the NIR region and have negative dielectric constants over all or part of this region. This technology can provide polymers with high visible transmittance while blocking the near infra-red and UV [3]. Clear gel sunscreens operate on a similar principle, the ZnO particles provide appropriate solar absorption while the nanosized particles render the sunscreen clear to visible wavelengths. Nanoparticle doped polymer films can be used as glazing in a number of ways; as a polymer layer laminated between the glass, as film fixed to the surface, or as a clear 'stand alone' polymer glazing. The first method has an attractive application to safety glass essential in automobiles and as used in many commercial buildings.

2.2. Angle Selective Technologies

Controlling angular transmission of a window system has been around for considerable time. Venetian blinds, awnings, eaves etc are all examples of this technology, albeit using shading elements separate from the glass window itself. Recent advances in this area seek to incorporate angular selectivity directly into the glazing. One method is to use polymer glazing panels possessing internal structure to divert light from specific directions [8]. Another technology, using a co-polymer with two refractive indices, provides clear transmission in some directions while scattering incoming light from others [9]. The scattering makes it impossible to view in certain directions but does not appear to provide energy control.

Ideally angular control should be combined with the spectral selectivity of the thin films described in the previous section. Oblique vacuum deposition of metallic or metal-insulator (cermet) layers can produce thin films with an ordered, inclined columnar structure. These films show anisotropic absorption due to the inhomogeneous nanostructuring [10]. Cermet films are particularly promising showing angular selectivity that extends well into the NIR region [11].

3. Some Results

Transmittance curves for three single layer TiN_x thin films with different stoichiometry are shown in Fig. 1 [12]. Shifting the transmission maximum to wavelengths around 600 – 650 nm by increasing the N/Ti ratio gives relatively neutral transmitted light. The films are prepared by magnetically filtered arc deposition assisted by N^+ ion bombardment This technique can produce films with N/Ti ratios as high as 1.3 while maintaining the metallic properties characteristic of stoichiometric TiN.. As well as shifting the transmission maximum, increasing the nitrogen content also decreases the screened plasma frequency. This quantity determines the onset of reflectance. Values range from 2.6 to 1.7 eV for N/Ti = 1.0 to 1.3 respectively. For the higher N/Ti ratios reflectance does not begin to rise strongly until the edge of the visible spectrum. By modelling the thin films on glass using the measured optical constants, spectral performance can be explored. For thicknesses around 13 nm single layer films can have T_{vis} in the range 40-60% and T_{sol} in the range 14-40%. Although this is not a major improvement over TiN films in itself, the transmitted light has neutral appearance. Using multilayers can improve the spectral performance, but the ability to improve transmittance may be limited by the absorptance for the TiN layers.

Nanoparticle doped polymers show good spectral control even at doping levels as low as 0.2% by weight. Fig 2 shows the transmittance of an undoped 0.7 mm thick polyvinyl butyral (PVB) layer laminated between two pieces of clear glass compared with the same laminated structure where the PVB is doped with indium tin oxide (ITO) nanoparticles [3]. It is clear from this figure that nanoparticle increases absorption in the IR, while hardly affecting visible transmission. The value of T_{vis} is virtually identical for both undoped and doped laminate, 0.88 and 0.87 respectively, while T_{sol} drops from 0.73 to 0.62. Even though the doped polymer is quite absorbing, A_{sol} being 0.34 compared with 0.19 for the undoped laminate, improved SHGC values are still achieved, compare 0.68 for doped with 0.78 for undoped. Antimony tin oxide (ATO) can also be used as the dopant and is cheaper than ITO but at the expense of some spectral performance.

Finally, Fig. 3 shows the performance of an angular selective film. This is an Ag / TiO_2 cermet film prepared by oblique deposition onto a glass substrate [11]. The TiO_2 is deposited by filtered cathodic arc with co-deposition of the metallic Ag by thermal evaporation. These films show good angular selectivity across a wide wavelength range, unlike most other films which only show this behaviour in the visible region. The colour properties of the transmitted light as a function of viewing angle also show some interesting properties, with a clear shift in colour between different incidence angles. The variation of angular transmittance with wavelength and the reversal of angular selectivity around 650 nm gives rise to this effect. Ag/TiO_2 films prepared by d.c. magnetron sputtering show reduced angular selectivity compared with the results in Fig. 3 [11].

Modelling plays a critical role in this work. Semi-empirical models can be used to model spectral response from experimental measurements of optical constants, and optimise the design of a given glazing system In addition, first principles calculations provide an understanding of the underlying physics and help to identify likely candidates for new technologies. For example, controlled spectral tuning of absorption using metal nano-shells on nanoparticles recently predicted by calculations [13]

4. Conclusion

There are a number of viable technologies for the production of energy-efficient glazing. They rely upon modifying the glass' transmission properties as a function of wavelength and / or angle of incidence. Ideally the glazing system should be virtually transparent in the visible part of the spectrum to afford optimum viewing while being strongly blocking in the near infra-red in order to reduce heating effects due to the transmitted radiation.

Complex multilayer thin film coatings of metallic and insulating layers provide good spectral performance in this regard. However, they are extremely expensive to prepare, a factor which has no doubt inhibited their widespread use.

Nanoparticle doped polymer films are a cheap and easy to prepare alternative. They are resonantly absorbing in the near infra-red if the dopant nanoparticles are made from a suitable material, and can match the performance of multilayer coatings. They are particularly attractive in application to laminated glazing systems such as in the safety glass of cars and commercial buildings. Angular selective cermet films prepared by oblique deposition can also provide a good degree of solar control and hence improve energy-efficiency in warm climates at a modest cost.

Acknowledgements

This work was supported by funds from the ARC and University of Technology, Sydney.

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Figure Captions

Fig. 1. Measured transmittance for TiN_x films of different stoichiometry.

Fig 2. Specular transmittance of glass-PVB-glass laminate versus laminate with ITO doped PVB layer.

Fig. 3. Transmittance of s- and p- polarised light at selected angles of incidence for a 100 nm thick Ag/TiO_2 film.