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Selective Windows for Indoor Thermal Comfort

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Abstract: Buildings in hot countries experience significant amount of heat gain through windows and this affects the thermal comfort of buildings' occupants. The proposed glazing is specially designed to reduce the electricity consumption for lighting and cooling. The optical properties of the glazing have been optimized by using rigorous coupled-wave analysis method. The glazing consists of ITO and four periodic pairs of Si/SiO_2, deposited on a glass sheet. The fabrication of the glazing and the testing has been performed at the laboratories of the Faculty of Science, University of Witwatersrand, South Africa. Magnetron sputtering technique has been used for the fabrication. The optimum thicknesses of ITO, Si and SiO_2, obtained from the simulation and the experimental work, are 0.1 µm, 0.15 and o.4 µm, respectively. The glazing transmits 70-80% of the visible light and reflects almost all the infrared radiation.

Keywords: smart windows, indoor thermal comfort, hot climates.

INTRODUCTION

People spend between 80% and 90% of their days indoors [1]. The building sector (residential, commercial and public) uses between 20% and 40% of final energy consumption. This is mainly for cooling and lighting. Architects and engineers think of ways to improve the environmental comfort inside the buildings. The windows represent the weakest point in the thermal performance of buildings. This work is a contribution to the indoor thermal comfort in hot climates, by introducing optically selective windows.

Human comfort is that condition of mind, which expresses satisfaction with the thermal environment and is assessed by subjective evaluation [2]. Ricardo *et al.* [1] reviewed the papers published in 10 years that examine the various subareas of research related to human thermal comfort. The results of review showed broader ranges of indoor temperatures. Between 19.5 and 25.5 ^{0}C, buildings may operate in free-running mode. Above 25.5 ^{0}C up to 28.0 ^{0}C and even 30.0 ^{0}C, the use of ceiling fans and personally controlled fans may guarantee thermal acceptability. In higher temperatures cooling is needed. The relationship between comfort temperature and outdoor temperature in naturally ventilated buildings was found to be linear, Taleghani *et al*. [3].

$$T_{co} = 0.31\, T_{ref} + 17.8\ ^0C \qquad (1)$$

Where
T_{ref} = prevailing mean outdoor air temperature
T_{co}= indoor comfort temperature

By improving the glazing performance of windows, it is possible to reduce the electricity consumption. This can be done by modifying the spectral selectivity of the glazing. At present, this has been achieved by using what is known as smart windows. The most popular types are the electrochromic and thermochroic windows. The optical properties of these materials are either electrically adjustable or thermally self-adjusting.

Electrochromic windows change light transmission in response to an external applied voltage. The transition from clear to opaque could take 3 - 5 minutes, for a small window [4]. Hong and Chen [5] used nano-Prussian blue analogue/ PEDOT/PSS: composites for a 10 × 10 cm^2 WO_3 electrochromic window. Maximum transmittance modulation of 61.6% at a voltage of 1.6 V was obtained. Kim and Taya [6] used V_2O_5 and poly (3,3-dimethyl-3,4-dihydro-2H-thieno[3,4-b][1,4]doxepin) coatings. The window demonstrated electrochemical stability after over 150,000 cyclic switches, and that the response time for a 25 × 25mm^2 window was 5 seconds for coloration and 4 seconds for bleaching. Similarly, Kim *et al.* [7] obtained high electrometric contrast and optical cyclic stability, when they used electrochromic windows based on anodic electrochromic polymesitylenes containing 9Hcarbazole-9-ethanol moieties. Fernandes *et al.* [8] used glass/ITO/WO_3/electrolyte/ITO/glass layered configuration. That resulted on visible average transmittance variation and optical density change of 41.6% and 0.39%, respectively. Hee *et al.* [9] concluded that electrochromic windows are more suitable for applications in residential areas in cold climate regions.

Thermochromic windows switch from a clear state in low temperature to a diffuse reflective state in high temperature. The results of Long *et al.* [10] indicated that, in hot climate, the use of VO_2 window decreases the energy consumption for cooling compared to the case with ordinary window. Zheng et al. [11] designed TiO2(R)/VO_2 (M)/TiO_2(A) multilayer film to work as a smart window with antifogging and self-cleaning functions. Koo *et al*. [12] fabricated CeO_2-VO_2 bilayer to improve the optical properties of VO_2 window. The CeO_2 was employed as an antireflection layer of the VO_2 film. Kamalisarvestani *et al*. [13] studied the spectral selective properties of thermochromics windows and the effect of doping of VO_2 coatings with different dopants.VO_2 could be the most promising thermochromics material, but its drawback is the preparation cost and the stability. Batista *et al*. [14] concluded that tungsten was the most effective dopant on the reduction of the semiconductor-metal transition temperature of VO_2. More energy could be saved by using VO_2 double window.

Both electrochromic and thermochromics windows suffer from high cost, low transmission of visible light and slow response time. In tropical regions, the ideal window is the one which transmits all the visible light, to reduce the lighting load, and reflects all the infrared radiation to reduce the cooling load, with 0.78 µm cutoff wavelength.

In this paper we present our work for designing and testing windows which could be more suitable for use in hot climates. They could reduce significantly the electricity consumption for cooling and lighting.

Theoretical Results

We studied the potential of using thin layers of periodic structure as a glazing with selective properties. The structure which has been designed and tested consisted of alternating layers of Si/SiO_2. The number of layers and the thicknesses of Si and SiO_2 were optimized by using rigorous coupled-wave analysis method.

Rigorous coupled-wave analysis (RCWA) is formulated in the 1980s by Moharam and Gaylord. It is used for analyzing the diffraction of electromagnetic waves by periodic gratings [15]. RCWA is used in this study to calculate the radiative properties (reflectance and transmittance) of the periodically multilayer surfaces. It analyzes the general diffraction problem by solving Maxwell's equations accurately in each of the three regions (input, multilayer, and output), based on Fourier expansion [16].

The glazing consists of ITO layer deposited on one-dimensional, four pairs of Si/SiO_2 layers on top of a 1mm-glassm sheet, Figure.1.The geometric parameters used to optimize the selective filter are the thicknesses of the layers. The wavelength-dependent dielectric optical constants of ITO, silicon and silicon dioxide were obtained from Ref [17].

At first, the thickness of ITO and SiO_2 were fixed at 0.1µm and 0.4µm, respectively. The thickness of Si was varied (d_1=0.1, 0.15 and 0.2µm). The reflectance and transmittance, at normal incidence, were calculated numerically by using RCWA method in the wavelength range from 0.3 µm to 3 µm. The results are shown in Figure.2 .The results show that the optimum thickness of the Si is 0.15µm.

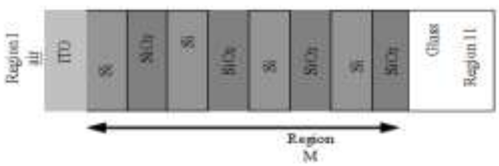

Fig-1: Selective filter components.

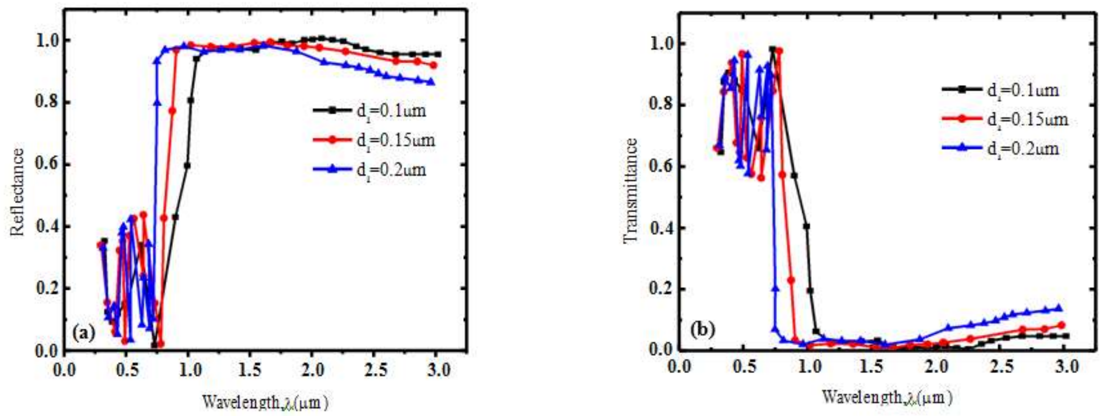

Fig-2: The proposed selective filter for wave with different thicknesses (d_1).of Si
(a) shows the reflectance and (b) the transmittance.

Figure.3 shows the reflectance and transmittance of the glazing at normal incidence. The thickness of Si was fixed at its optimum value (0.15μm), while that of SiO_2 was changed, d_2 = (0.2, 0.3 and 0.4) μm. The results show that the optimum thickness for SiO_2 is 0.4μm. The figure shows that when the sickness of Si is chosen to be 0.15μm and that of SiO_2 to be 0.4μm, the glazing transmits 70-80% of the visible light and reflects almost all the infrared radiation.

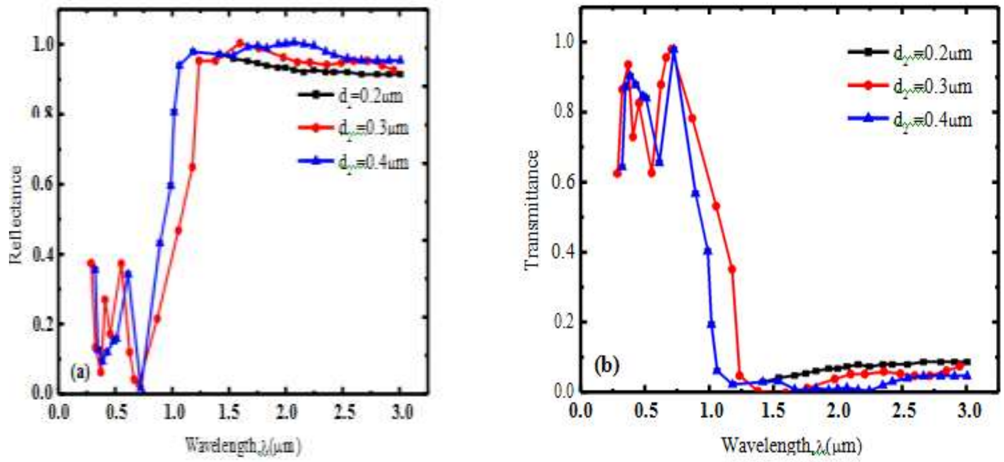

Fig-3: The glazing with different SiO_2 thicknesses (d_2)
(a) shows the reflectance and (b) the transmittance.

The glazing not only reduces the electricity consumption during daytime, but it also acts as an insulator during the cold nights of winter. It reflects the heat back inside the room. In the desert, the air temperature drops to less than 10 ^{0}C during the night. When the room temperature is about 30 ^{0}C, which corresponds to a peak wavelength of about 10 μm, there would be very little heat loss through the windows, Fig.4.

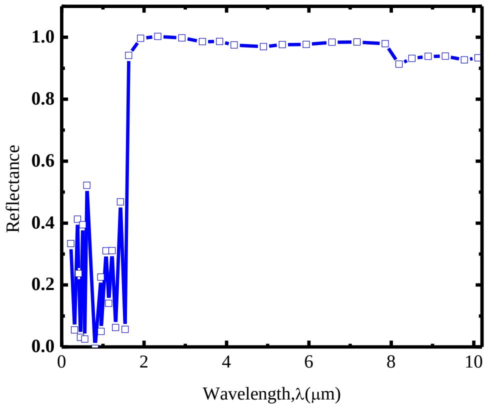

Fig -4: The optical properties of the glazing in the infrared range make it a potential insulator during the cold nights

The effect of the angle of incidence on the reflectance and transmittance is shown in Fig. 5. It is seen that increasing the angle of incidence from 0^0 to 60^0 makes little difference on the reflectance and transmittance. The glazing seems to be suitable for all seasons and for both direct and diffuse radiation.

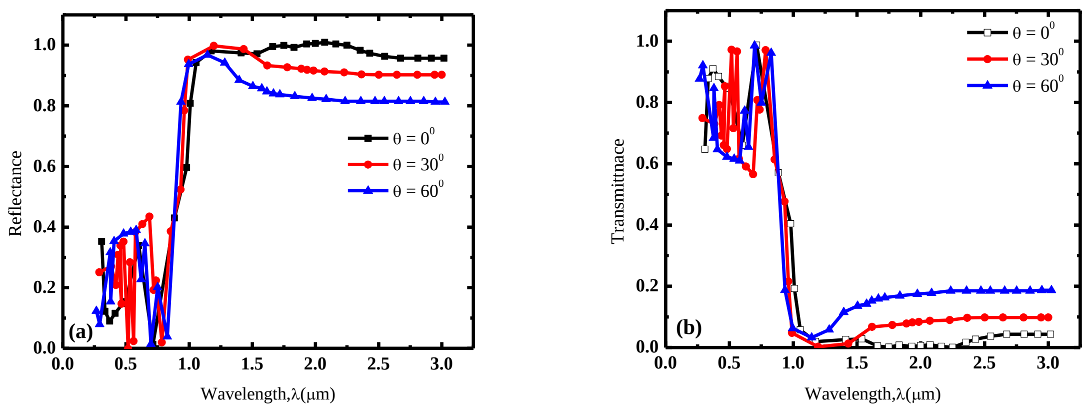

Fig-5: The performance of the glazing for different incidence angles. (a) Reflectance and (b) transmittance

Experimental Results

The fabrication of the glazing and the testing were performed at the laboratories of the Faculty of Science, University of Witwatersrand (Wits), South Africa, by using magnetron sputtering technique. The glass was cleaned in an acetone, rinsed in de-ionized water several times and then inserted into the sputtering chamber. The substrate temperature and the chamber pressure were maintained at room temperature and 6.5×10^{-4} pa, respectively. The distance between the sputtering target and the substrate was about 5 cm.

The sputtering gas, which was used in the system, was argon. The sputtering chamber was heated to 350 °C for 60 minutes before the sputtering process, to get rid of the water vapor at the walls and also to improve the film adhesion on the substrate. Indium tin oxide (ITO), silicon (Si) and silicon dioxide (SiO_2) were used as sputtering targets. The glazing consists of ITO layer and four pairs of Si/ SiO_2layers, deposited on top of a 1mm-glass sheet. The magnetron sputtering system was used to deposit a thin film from sputtering targets onto the substrate.

First, indium tin oxide was deposited on top of a 1mm-glass sheet substrates for 10 minutes and then alternating layers of Si/ SiO_2 were deposited on top of the ITO. Si and SiO_2 were deposited at different thicknesses, for comparison with the simulation results. The amount of material sputtered from the target and deposited onto the substrate and the deposition time was recorded.

The spectral transmittance and reflectance system consists of a powering system, light source, stepper motor, photo-detectors and analog to digital converter. The light source consisted of a fluorescent lamp (250V, 25W) and a holographic grating (1200 lines/mm), which was placed in focus to the light. A concave mirror of focal length 5 cm was mounted on a shaft of a gear system driven by a stepper motor of resolution 3.75°, focuses monochromatic beams vertically on the sample. The focusing concave mirror was mounted to a unipolar stepper motor, power rated (500mA, 24V), which was used to control small angle of rotations of the mirror. The first photo-detector received the beam through computer controlled small angular rotations of the stepper motor. The reflected monochromatic beam from the probed thin film sample was directed to the second photo-detector and the intensities of both the incident and reflected beam were then converted to digital form by analog to digital converter, connected to enhanced parallel port, used in computer interfacing.

The results of the measurement of the reflectance and transmittance are shown in Figure6.The thickness of the Si, d, was taken to be 0.1, 0.15 and 0.4μm. The thickness of SiO_2 was fixed at 0.4μm and that of ITO at 0.1μm.The results show that the optimum thickness for Si is 0.15μm. This agrees with the simulation results.

When using the optimum thicknesses, the glazing transmitted about 78% of the visible light and reflected nearly all the infrared radiation. The values are similar to that from the simulation results.

The experimental results confirmed that the glazing can easily be fabricated and that it satisfies the thermal comfort of the occupants of the buildings in hot countries. By transmitting most of the visible light and reflecting most of the heat, it reduces the electricity consumption for lighting and cooling.

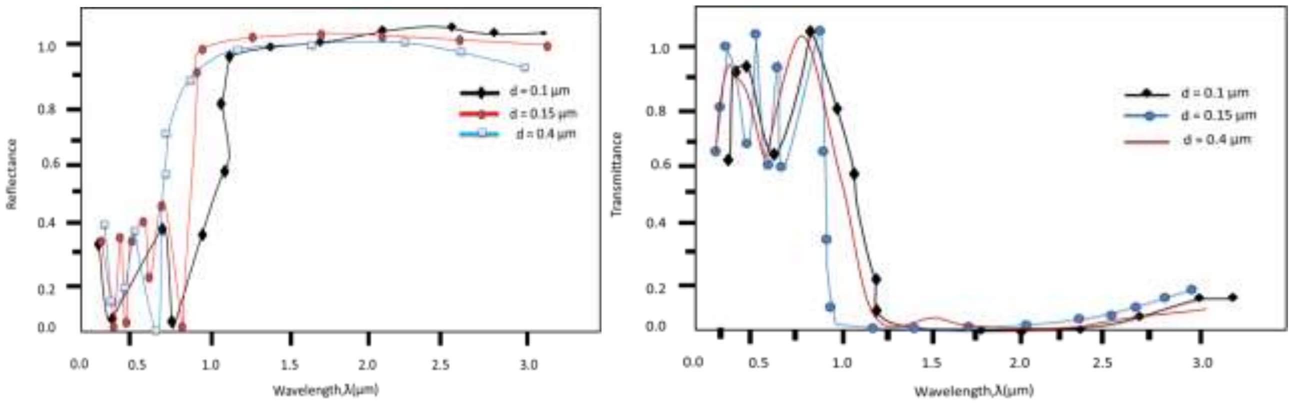

Fig-6: Reflectance and transmittance of the filter

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