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Chemical vapour deposition of thermochromic vanadium dioxide thin films for energy efficient glazing

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ABSTRACT

Vanadium dioxide is a thermochromic material that undergoes a semiconductor to metal transitions at a critical temperature of 68 °C. This phase change from a low temperature monoclinic structure to a higher temperature rutile structure is accompanied by a marked change in infrared reflectivity and change in resistivity. This ability to have a temperature-modulated film that can limit solar heat gain makes vanadium dioxide an ideal candidate for thermochromic energy efficient glazing. In this review we detail the current challenges to such glazing becoming a commercial reality and describe the key chemical vapour deposition technologies being employed in the latest research.

1. Introduction

In the modern world there is a constant and ever increasing demand for energy. This demand is having a marked effect on both the environment of the planet, in the form of increased global warming and the health of the people living in it. This is due to decreased air quality and increased solar radiation exposure due to ozone layer depletion and subsequent demand for cooling. This means that burning more fossil fuels is not a viable way to meet these demands leading to a growing demand for the development and implementation of renewable energy sources to stop the emission of green house gasses such as CO_2. One way in which this problem can be reduced is by the introduction of better energy efficiency in buildings. As windows tend to be the greatest thermal sink for buildings the chemical vapour deposition (CVD) process is an ideal way to produce glazing that could reduce this loss [1]. The current solutions to the window heat loss issue tend to be a use of multiple layer glazing (triple or double) with a static glazing and possibly inert gas filled layers. There is also the possibility of using electronically controlled blinds. In general there are three main type of climate that need separate consideration for solar control:

Cold Climate e.g. *Scandinavia:* Low thermal transmittance (U) with high total solar transmittance (T_s), e.g. triple glazed, argon filled with 2 low-E coatings giving U=0.95 W m^{-2} K^{-1} and T_s=0.5.

Hot Climate e.g. *Southern Europe/North Africa:* Solar control with low thermal transmittance and high visible transmittance (T_{vis}), e.g. double glazed, argon filled with 1 spectral selective coating giving U=1.35 W m^{-2} K^{-1}, T_s=0.37, T_{vis}=0.67.

Variable Climate e.g. *Northern Europe or Northern America:* Combination of hot and cold, with variable visual/solar control achieved by encapsulated blinds (commercially available) or electrochromic/thermochromic glass (not yet commercially available) [2].

It is variable climates that are the main focus of this review as the vast majority of the world's population live in areas where in summer the ambient temperature is higher than 20 °C and lower than 20 °C in winter. In these cases a dynamic approach to solar gain control is ideal that is to say one that will limit/reduce solar gain in the summer and maximise it in the winter.

1.1. Current challenges

In recent years there has been a drive to increase the energy efficiency of buildings for both economical and environmental reasons. The greatest source of energy consumption in buildings results from the use of climate control devices (heating, ventilation and air conditioning (HVAC)) [3]. Increasingly larger areas of the world are being developed with buildings built to modern standards of living that dictate demand for air conditioning in hot climates and heating in cold climates. These new builds will continue to increase, driving the world's energy demand and consumption higher. As the use of climate control devices increases the use of electricity, this subsequently effects the level of CO_2 released it means that the global warming problem will

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increase and therefore cause more climate control setting up a cycle as shown in Fig. 1.

1.2. Current approaches

Modern solutions to the climate control energy demand involve the use of either, more efficient HVAC systems or, increased levels of insulation to reduce the loss from current HVAC systems. Walls and roofs are reasonably straight-forward to insulate as cavities can be filled with insulation foam and extra layers can be added. Windows, however, are not as straightforward as they must be transparent.

Windows serve two main functions; a source of light and a visual aesthetic with the outside world [4]. Modern architectural design has lead to many buildings being constructed with large glass facades while this is aesthetically pleasing and space efficient it does make these buildings far more susceptible to thermal inefficiency.

There have been studies done into the effectiveness of different forms of energy saving methods on houses in a very controlled environment one such example of this is set out in Fig. 2. The so called “Passive House” is a highly efficient building standard first developed in Germany in the last few decades, under the name “Passivhaus”, in which the main criteria is that the building requires no more than 15 kW h of useful heat per year per square meter [5]. This value corresponds to a 90% reduction in heating compared to existing buildings. The main physical characteristics of buildings have been considered during the passive house development.

From these first experiments four main points were discovered that are key to reducing a buildings energy usage:

1. Excellent thermal insulation, including the avoidance of thermal bridges, and low window heat losses.
2. A very airtight building envelope.
3. A ventilation system with highly efficient heat recovery.
4. The passive use of solar energy.

Two of the key methods found to improve thermal energy efficiency have a direct link to window glazing these are; (1) excellent thermal insulation, including the avoidance of thermal bridges, and low window heat losses, (2) the passive use of solar energy. It can be seen from Fig. 2 that the windows account for the greatest losses as well as some of the largest gains in thermal energy to/from the building and there is therefore a drive to improve this aspect of the buildings architecture.

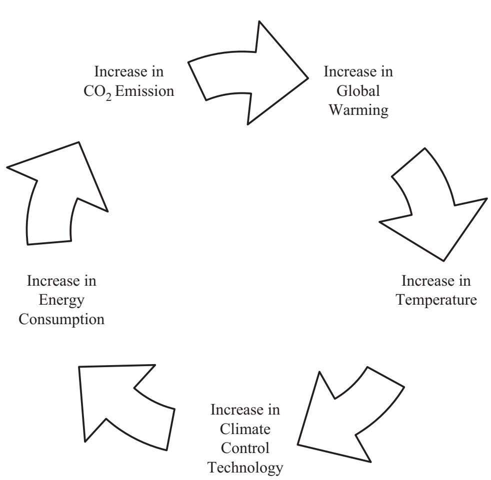

Fig. 1. Schematic of the energy cycle set up by increased usage of climate control devices.

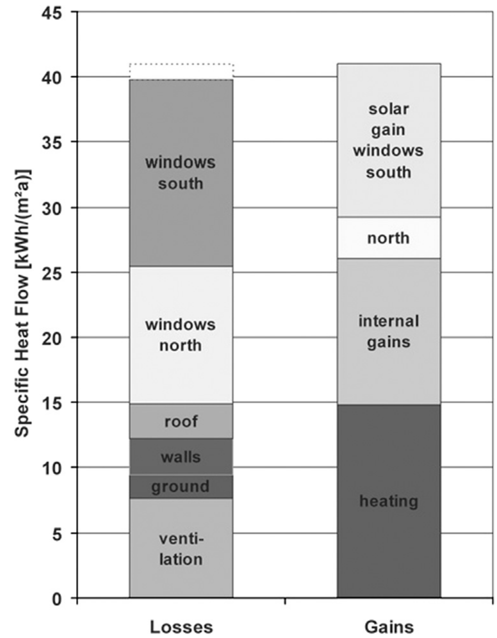

Fig. 2. Typical energy balance of Passive house during the heating period [5].

1.3. Possible glazing solutions—Thin films for solar control

As the windows are the source of such potential gain and also loss of energy to a building it is important to find away to improve their thermal efficiency without compromising the natural lighting and visual aesthetic that they provide to a building.

1.3.1. Static metal oxide films

There are three main types of static film available these are:

1. Low emissivity (low E) films.
2. Spectrally selective thin films (heat mirrors).
3. Absorbing layers.

1.3.1.1. Low E films. Low emissivity films (Fig. 3) are usually composed of a metal oxide thin film and reflect the far infrared (black body radiation $\lambda > 3000$) radiation. These films are a static coating that are best suited to use in areas with a cool climate where heat needs to be trapped within the building as black body radiation corresponds to the heat reemitted within a building rather than the incoming solar radiation. The ideal properties for a low E film are Transparency in the $300 < \lambda < 3000$ nm range and reflecting at values where $\lambda > 3000$ if these criteria are met it allows heat to be trapped within a building.

1.3.1.2. Heat mirrors. Heat mirrors are thin films typically composed of layers of metals and metal oxides these films are a static film, which are most efficient in hot climates. For a heat mirror to be of maximum efficiency it should have properties such that the visible region of the spectrum ($400 < \lambda < 700$ nm) has a 100% transmittance ($T_{vis} = 1$) and 0% reflectance ($R_{vis} = 0$) also the infrared region ($700 < \lambda$) should have $T_{IR} = 0$ and $R_{IR} = 1$ this ideal spectrum is shown in Fig. 4.