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An Infra-red Reflecting Optical Coating for Solar Cover Glass

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***Abstract*—A major problem with silicon solar cells is that they lose efficiency with increased operating temperature, at a rate of about 0.5% per 1°C increase. This causes a significant reduction in power output, particularly in hot climates. A solution in the form of an optical coating is presented, which reflects infra-red (IR) radiation to limit the module temperature increase. The optical coating is also anti-reflecting (AR) in the visible wavelength range, increasing the amount of light reaching the cell absorber. Modelling results show that the weighted average reflection (WAR) is reduced to 1.22% in the wavelength range associated with the band gap of silicon. The optical coating then reflects up to 70% of the infra-red. Although the model presented is based on silicon, the coating design can be modified to work with other photovoltaic technologies. The coating design uses only 4 layers and can be deposited using conventional high throughput magnetron sputtering systems already familiar to glass manufacturers. Preliminary work on optimising the coating deposition parameters is also presented here alongside modelling results. Deployment of the infra-red reflecting optical coating on solar cover glass represents a potential breakthrough in solar technology and will result in a significant increase in the power output of photovoltaic modules.**

***Index Terms*—photovoltaics (PV), antireflection (AR), infra-red (IR) reflection**

I. INTRODUCTION

The deployment of renewable sources of energy, such as solar photovoltaics (PV), is expanding rapidly due to increasing concerns about climate change and global energy security. The PV market is dominated by silicon, which accounts for more than 90% of current worldwide manufacturing capacity[1]. A significant problem with silicon solar cells is that they become less efficient at higher operating temperatures, losing ~0.5% efficiency per 1°C increase. For other commercial PV technologies such as thin film copper indium gallium selenide (CIGS) and cadmium telluride (CdTe) the losses are lower, at 0.36% and 0.21% respectively[2]. This loss of efficiency with increasing temperature is known as the temperature coefficient. Reduced efficiency at higher operating temperatures is a serious problem for silicon PV since modules installed in warmer climates can easily reach working temperatures of ~65°C[3] and potentially even higher. A crystalline silicon solar cell operating at 65°C would be 20% less efficient (relative) than its nominal value under Standard Test Conditions (STC), leading to a significant reduction in power output.

The loss of efficiency caused by increased operating temperatures is partly an intrinsic property of the semiconductor used in the solar cell, as a result of reduced bandgap and open-circuit voltage (V_{OC})[4], which cannot be addressed directly. Therefore addressing this issue requires a means of limiting the temperature increase itself. Although the temperature coefficient is well known[5], the impact of temperature has often been overlooked because module efficiency values are generated under STC at 25°C. Reduction of the module operating temperature via methods such as external cooling using closed loop re-circulating water[6] would work, but this would introduce significant cost, complexity and energy use, especially so in areas such as the Middle East where water is scarce and expensive.

In this paper, we introduce a new optical coating concept that is relatively simple and manufacturable[7]. The optical coating is designed to be deposited onto module cover glass so that it is anti-reflecting (AR) in the wavelength range used by the solar absorber but reflects infra-red (IR) radiation. This will increase the intensity of the light reaching the absorber whilst at the same time limiting the increase in the module temperature. IR photons beyond 1150nm do not contribute to the power output of the solar cell and impart their energy only as heat. In this paper we consider the AR effect tailored to the band gap of silicon. A simple 4-layer coating design using a combination of high and low refractive index materials that exhibits both IR reflecting and AR properties would be a relatively simple and cost-effective solution to the problem of efficiency losses due to increased operating temperatures. The multilayer design can be modified to provide optimised performance for other PV technologies including thin film CdTe and GIGS.

The modelled performance of the optical coating using a commercial optical modelling software package is presented, as well as details of the coating deposition technique. Preliminary work on the optimisation of ITO thin film deposition is also reported.

II. OPTICAL COATING DESIGN

Multilayer broadband anti-reflection coatings consist of alternate layers with low and high refractive indeces with specific layer thicknesses. Silicon dioxide (SiO_2) is almost always used for the low refractive index material, with a refractive index (n) of 1.47 at a wavelength of 550nm. Various dielectric metal-oxides are available for the high refractive index material, with zirconium dioxide (ZrO_2) and titanium dioxide (TiO_2) often used in high-volume applications due to their lower cost.

The design and performance of multilayer broadband anti-reflection coatings for the glass superstrate used for CdTe solar cells using 4 alternate layers of ZrO_2 and SiO_2 has been described elsewhere[8]. The outstanding durability, scratch resistance and temperature stability of these coatings has also been reported [9], [10]. Multilayer anti-reflecting coating designs for other photovoltaic technologies have also been described[11].

In this study, indium tin oxide (ITO) has been identified as an alternate high refractive index layer. ITO has the additional benefit of enabling the reflection of infra-red wavelengths longer than 1300nm. A simple 4-layer coating design provides AR within the band gap of silicon and reflection in the IR beyond the band gap.

A. *Optical Coating Design*

ITO is suitable for the combined AR/IR coating as it has a high refractive index in the visible wavelengths and a lower refractive index in the IR. The dispersion of the optical constants refractive index (n) and extinction coefficient (k) for ITO used in the present model are shown in Figure 1.

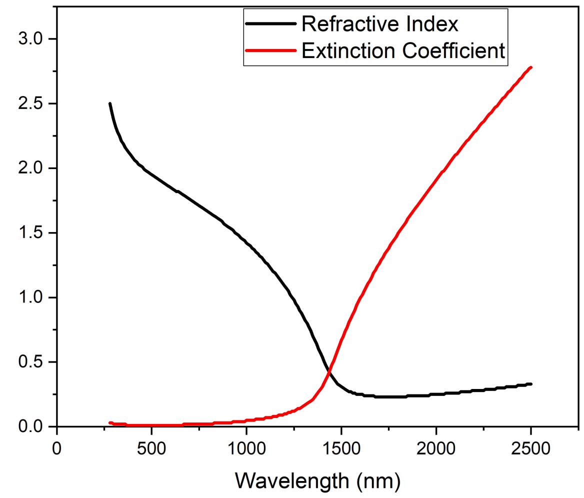

Fig. 1: The optical constant (n and k) dispersions for indium tin oxide (ITO) used in the multilayer design.

Refractive index data were imported into the optical modelling suite Essential Macleod, which was then used to investigate and optimise the number of layers, layer thicknesses and associated reflectance curves for the modelled coatings[12]. The dispersions for SiO_2 used in the model are shown in Figure 2. A schematic diagram of the 4 layer SiO_2/ITO design is shown in Figure 3. The total thickness of this design is only 274.4nm (see Table 1). The performance of the coating could be further improved by adding more layers, for example by creating a dielectric mirror using a stack of high/low refractive index pairs. A structure like this however would consist of around 20 layers[13], adding significant materials cost and manufacturing time, thus making it less likely to be adopted by manufacturers. A 4-layer design using SiO_2 and ITO provides a compromise between performance, ease of manufacture and cost.

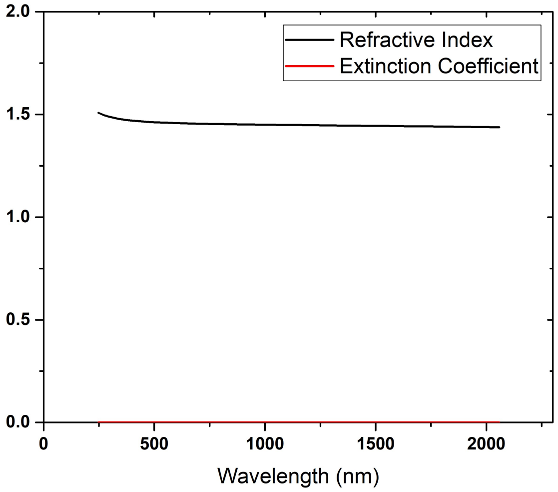

Fig. 2: The optical constant dispersions for silicon dioxide (SiO_2) used in the multilayer design.

Layer	Material	Thickness (nm)
Medium	Air	
1	SiO_2	87.9
2	ITO	142.7
3	SiO_2	25.2
4	ITO	18.6
Substrate	Glass	

TABLE I: The materials used in each coating layer and their respective thicknesses

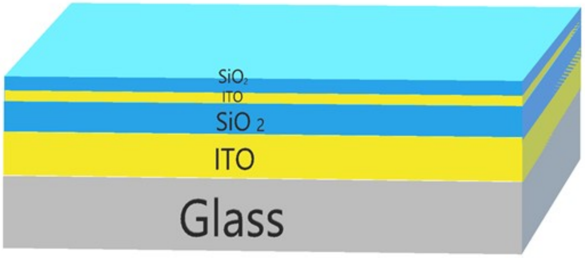

Fig. 3: A diagram of the coating design deposited on solar cover glass (not to scale)

B. *Reflectance Modelling*

The modelled reflectance curve for the coating across the wavelength range of interest is presented in Figure 4. The reflectance of the uncoated cover glass is also plotted, to show the increased transmission across the visible range. The weighted average reflection (WAR) in the 350-1100nm wavelength range is reduced to 1.24% with the coating, compared to 4.22% for uncoated cover glass. This allows almost

3% more sunlight into the cell, increasing the power output proportionately. The reflectance of the coating increases significantly above 1300nm, peaking at 70%. This increased IR reflectivity has the potential to limit the temperature increase of the module, thereby helping to mitigate efficiency losses due to increased operating temperature.

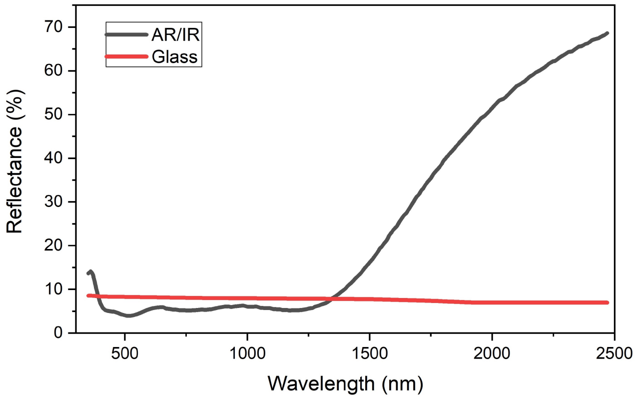

Fig. 4: The modelled reflectance of the coating design shown in Figure 3 when deposited on glass

C. Metal-oxide Deposition

The AR/IR multilayer coating is deposited using pulsed DC magnetron sputtering, in a My Coat deposition system supplied by Visionease Inc (Ramsey, MN). The machine is equipped with two magnetrons and a plasma source. The substrates are mounted on to a vertical carrier and inserted into a vacuum load lock. Once a pre-determined pressure is achieved in the load lock, the substrate carrier is automatically introduced into a separate deposition chamber. The loading time into the deposition chamber is typically less than 5 minutes. This substrate entry strategy provides high sample throughput. The pre-process background pressure is typically $1\text{x}10^{-6}$ Torr. The magnetrons are powered using a 5kW Advanced Energy Pinnacle Plus pulsed DC supply. The substrate carrier is set to rotate at 100rpm and thin film deposition follows an initial oxygen/argon plasma clean for 30 seconds to activate the substrate surface and promote adhesion.

The magnetrons are supplied locally with argon working gas while the plasma source is supplied with oxygen. The magnetrons and the plasma source are physically separated into deposition and reaction zones as illustrated schematically in Figure 5. The separation is achieved by situating the turbomolecular pump above the plasma source and by inserting vanes on to the carrier in close proximity to the cylindrical chamber wall. In this way, the magnetron can be operated without target poisoning in metal mode which enables high deposition rates to be achieved. A thin layer of metal is deposited in each pass of the carrier and this is then fully oxidised in its path through the oxygen plasma.

ITO is conductive which enables an ITO compound target to be used. Oxygen loss during sputtering can be compensated for by using low flow rates of oxygen in the plasma source. Manipulating the oxygen flow rates provides some control over the optical and electrical properties of the deposited thin films.

III. EXPERIMENTAL

A. ITO Thin Film Deposition

ITO thin films were deposited on 5cm x 5cm soda-lime glass substrates using pulsed-DC magnetron sputtering, as described above. All thin films in this work were deposited at room temperature. The substrate temperature increases on exposure to the magnetron plasma but is unlikely to exceed 50°C. The targets used were 6-inch diameter compound ITO targets. Glass substrates were cleaned in a solution of deionised water and acetone (with a 3:1 ratio) for 10 minutes in an ultrasonic bath prior to coating. Substrates were then mounted vertically on to the substrate holder, which has a capacity of 6 substrates mounted on facets. An image of a loaded substrate carrier is shown in Figure 6.

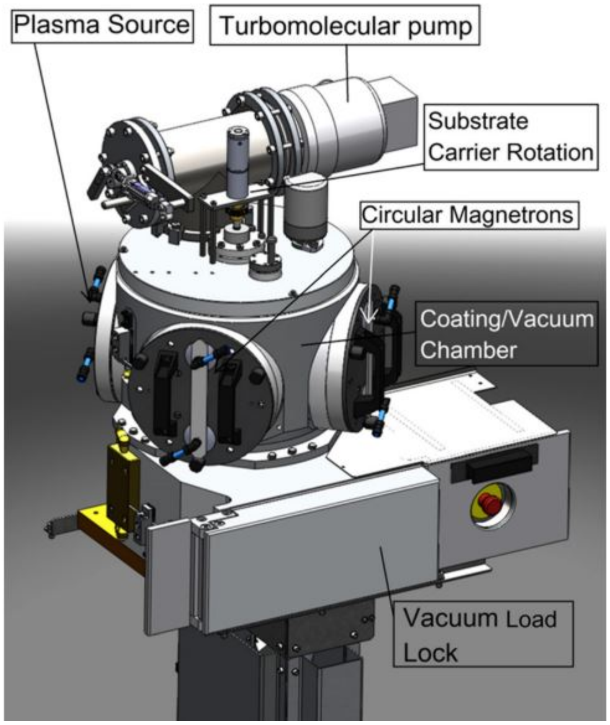

Fig. 5: 3D schematic of the sputtering system used to deposit the coating

Oxygen flow rates of 0.5, 1, 2 and 4 Standard Cubic Centimetres per Minute (SCCM) were investigated, with the argon flow maintained at 20SCCM. The gas flow rates were controlled using mass flow controllers. Deposition time was 300 seconds for all thin films. The power to the target was set at 1500W, with a pulse frequency of 150kHz and reverse time of 1.5μs. All deposition parameters are computer-controlled.

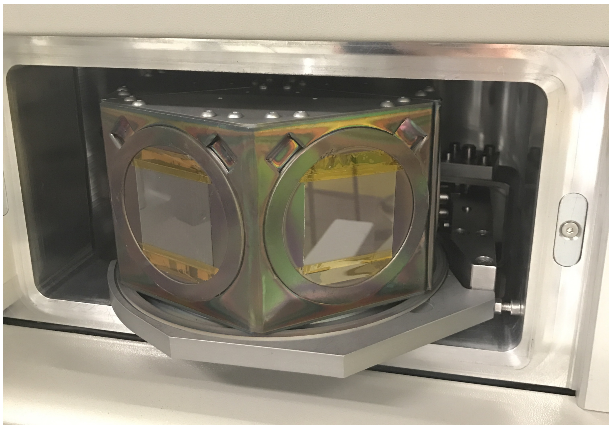

Fig. 6: Glass substrates mounted onto the substrate carrier

B. Electrical & Optical Characterisation of ITO thin films

The carrier density, mobility and resistivity measurements of the deposited films were taken using an Ecopia HMS-3000 Hall effect measurement system. Film thickness was determined using an Ambios XP-2 stylus profilometer. Transmission measurements were taken over a wavelength range of 200-2000nm using a Varian Cary5000 UV-VIS spectrophotometer. Refractive index data over a wavelength range of 250-2100nm were extracted using an Horiba JobinYvon UVISEL spectroscopic ellipsometer.

IV. RESULTS & DISCUSSION

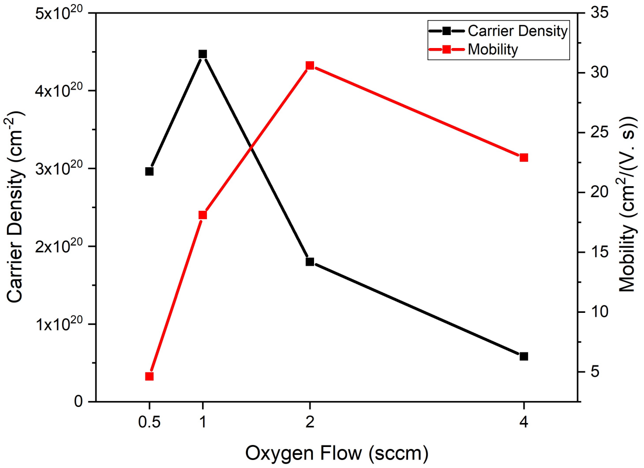

Fig. 7: Carrier density and mobility with varying oxygen flows for as-deposited films

Hall effect data for the as-deposited ITO thin films are presented in Figures 7 and 8. Carrier density reaches a maximum value of 4.47x10^{20} cm^{-2} at an oxygen flow of 1SCCM, where resistivity reaches a minimum value of 7.73x10^{-4} Ω·cm. The highest mobility, of 30.6cm^2/V·s is obtained using a flow rate of 2SCCM. The carrier density generally increases with decreasing oxygen content because the number of oxygen vacancies in the film is increased, leading to higher numbers of free electrons[14]. An oxygen flow of 0.5SCCM is too low to improve carrier density further as it leads to severe oxygen deficiencies degrading the materials crystal structure. A high carrier density results in higher IR reflectivity, making it an important parameter in the optimisation of ITO films for the AR/IR coating design. An oxygen flow of 1SCCM gives the most desirable electrical properties for the as-deposited ITO thin films.

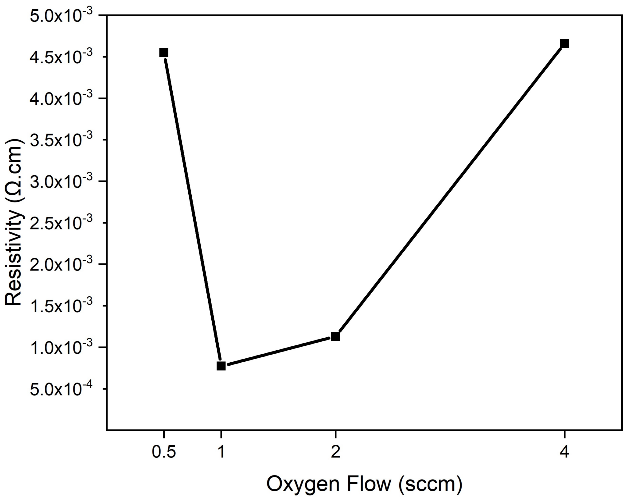

Fig. 8: Resistivity values with varying oxygen flows for as-deposited films

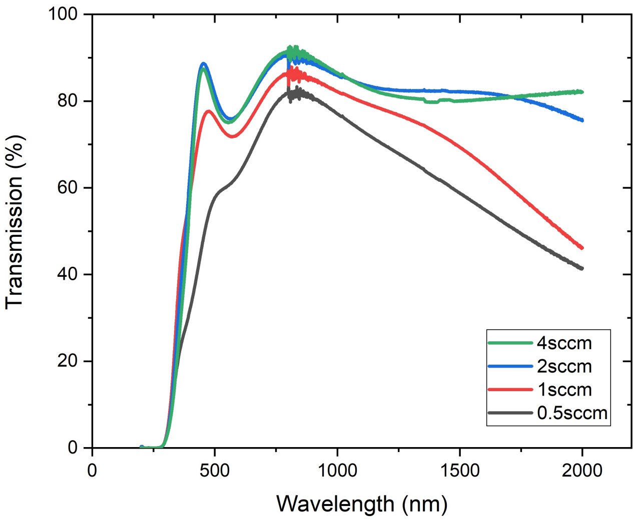

Fig. 9: Transmission curves for as-deposited films with varying oxygen flows

Figure 9 shows optical transmission curves for the as-deposited films. Transmission generally decreases with decreasing oxygen content, with a more prominent change observed towards the IR region. This decrease in transmission towards the IR is largely a result of increased carrier density, as shown in Figure 7. The shoulder observed in the curve for the film deposited with a 0.5SCCM oxygen flow at a wavelength close to 500nm may be caused by a breakdown of the crystalline properties as a result of severe oxygen deficiency, leading to higher absorption. Although the film deposited at 0.5SCCM exhibits the lowest transmission in the IR, the presence of severe oxygen deficiencies and increased absorption leads to the optimum film being that deposited under an oxygen flow of 1SCCM, which is in agreement with the electrical properties.

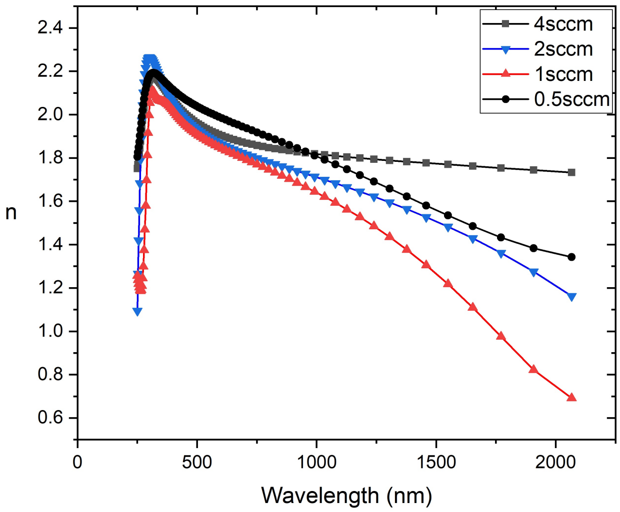

Fig. 10: Refractive index (n) dispersions for the as-deposited films with varying oxygen flows

Figure 10 shows the refractive index dispersions for each of the as-deposited films. The ideal dispersion required to achieve optimum performance of the coating is one that has a refractive index higher in the visible wavelengths, and which then reduces dramatically as it approaches the infra-red, as demonstrated in Figure 1. The dispersion produced by an oxygen flow of 1SCCM is the closest to this ideal in this set. The dispersions produced by the other oxygen flows do not achieve the desired drop in refractive index at longer wavelengths.

For deposition at room temperature, the optimum oxygen flow for as-deposited samples appears to be 1SCCM, with the thin films showing relatively low transmission in the infra-red regions and the high carrier density whilst maintaining its crystalline properties. The achieved refractive index dispersion is closest to the optimum dispersion used in the model. However, it is likely that the dispersion, as well as the electrical properties, could be further improved by depositing at elevated substrate temperatures and/or by post-deposition annealing.

Figure 11 shows the modelled AR/IR curve from 250-2100nm using the ITO deposited under an oxygen flow of 1SCCM, and the original model from Figure 4. The modelled curve exhibits similar AR effects below 1100nm, however there is very little IR reflection when compared to the original model. The low IR reflection is likely caused by the low carrier density in the deposited films. Significant improvements in carrier density are required in order to reach the level of performance predicted in the original modelled curve.

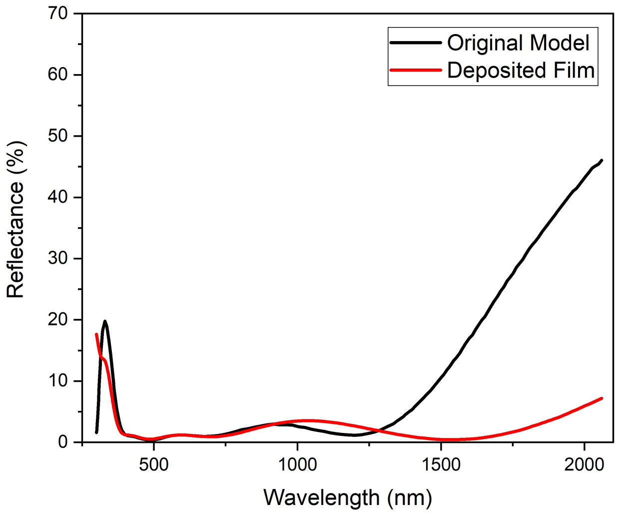

Fig. 11: Modelled reflectance curves from 250-2100nm for the deposited ITO and that of the original model

With most commercial PV technologies already well-established, increases in conversion efficiency by improving the semiconductor or device performance are now mostly iterative. This paper addresses the temperature coefficient of PV absorbers with a particular focus on silicon.

A combined AR/IR-reflecting coating for solar cover glass represents a possible breakthrough in mitigating a major source of efficiency loss in PV modules. The coating comprises only 4 layers of alternate ITO and SiO_2 and has a total thickness of $\sim$275nm.

Both these materials lend themselves to high throughput manufacturing techniques such as magnetron sputtering. Magnetron sputtering is already used to produce optical heat reflecting coatings by major glass manufacturers. Early adoption of the coating technology presented here would be possible through simple adaptation of existing coating platforms.

The increased power output from PV modules deploying this coating will reduce the cost of electricity generated. A significant reduction in module operating temperature could also improve the lifetime of the module, as temperature is one of many factors responsible for degradation. For example, higher operating temperatures have been associated with cyclic stresses in PV modules that can propagate microcrack growth [15] as well as degradation of the EVA encapsulant found in most commercial silicon modules[16]. Improvements in module lifetime will further decrease the levelized cost of electricity (LCOE) produced by solar panels. Although electrical properties have not been directly optimised, the incorporation of ITO, a transparent conductor, will also make the module surface anti-static which will help to mitigate soiling, another significant source of losses in power output of PV modules[17].

The optical coating design presented in this work is optimised for the band gap of crystalline silicon cells, however the design is tuneable and can be made to work for other PV technologies.

V. CONCLUSIONS

Using ITO as the high refractive index material in a multilayer broadband AR coating enhances IR reflectivity. Such a coating would lower the operating temperature of PV modules and mitigate efficiency losses. Modelling results show a peak IR reflection of up to 70% is possible along with a reduction in weighted average reflection (WAR) in the visible from 4.22% to 1.24%, increasing light transmission and subsequent power output.

Optimisation of the deposition conditions of the ITO layers is crucial to achieving the modelled coating performance. Preliminary work has been undertaken to optimise the deposition conditions of ITO thin films, with an oxygen flow rate of 1SCCM providing the most desirable optical and electrical properties. Significant improvements in carrier concentration and refractive index dispersion are still required to achieve the level of performance predicted by the model.

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