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Interference Pigment Coated Solar Cells for Use in High Radiant Flux Environments

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Abstract

We describe our development of heat-resistant solar cells made by depositing the interference filter pigment Solarflair on the surface of silicon and compound semiconductor solar cells. The coating is designed to reflect long wavelength components of solar radiation while admitting shorter wavelength visible and near-infrared components. This results in less heating of coated cells as compared to uncoated cells and consequently their maintaining high light-to-electricity conversion efficiency. Such coated cells have the potential to be usefully employed in concentrator type photovoltaic array systems. Details of the interference pigment used, coating techniques and results of measurements in simulated high heat load environments are described.

Keywords: Solar cells, Thermal Protection, Protective Films, Interference Pigments.

1. Introduction

With the proliferation of solar photovoltaic technology in recent years both the number and diversity of solar power installations has been increasingly rapidly. The emphasis on environmentally friendly i.e. green energy technologies has provided a big impetus to the development of semiconductor solar cell technology. A number of materials such as silicon, gallium arsenide and cadmium telluride have been used for the manufacture of solar photovoltaic cells[1]. Organic solar cells are also seeing a surge of interest even though their conversion efficiencies are significantly below that of inorganic cells. Silicon, however, remains the most popular material for solar cells and its prevalence in the industry will likely remain for at least several years to come. When used for solar photovoltaic applications distinction is usually made between monocrystalline, polycrystalline and amorphous silicon solar cells as these are very different from each other in terms of cost of production and power conversion efficiency. In general, compound semiconductor solar cells are more efficient than silicon solar cells in converting the energy in sunlight to electrical power. Again, monocrystalline silicon cells are more efficient that polycrystalline cells which are still more efficient than amorphous silicon cells. No matter which material technology is used for the construction of solar cells their efficient operation is dependent on their receiving an optimum amount and type of incident radiation. While large incident flux is usually desirable there is increasing realization that too high an intensity of solar radiation can lead to diminishing returns by heating up cells and thus causing loss of power conversion efficiency as well as a reduction in the cells useful lifetime. Selective spectral filtering of sunlight can go a long way towards addressing these issue and our work demonstrates that by forming appropriate filter coatings on the surface of solar cells it is indeed possible to make them more efficient under high input flux situations. This essentially implies an increase in cell operating efficiency and thereby a gain in overall electric power production. This issue will assume even more significance in the next few years when concentrator type solar cell installations become more widespread[2]. Concentrator solar cells have to endure much higher temperatures than cells simply exposed to the sun in large panels and their efficiency and lifetime can be greatly improved with this technology. We go on to describe the characteristics of our filter films and their effect on the operation of both GaAs and Si solar cells.

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2. Interference Pigments as Sunlight Filters

Incident light can be filtered in either intensity or wavelength by using either absorptive pigments or interference pigments. Transparent coatings containing ordinary colouring pigments have long been used for customising light for a variety of applications. Examples range from sun glasses to filters on infrared remote controls. In recent years, however, the idea of using interference pigments as light filters has gained much ground. These pigments are essentially small coated particles that act as multi-layer dielectric filters[3]. Instead of using the usual method of forming dielectric filters by depositing materials of appropriate refractive index on plane glass or other flat transparent substrate, interference filters are made by the chemical deposition of transparent oxides on particles of quartz or mica. By carefully sequencing and controlling reaction conditions it is possible to deposit a multi-layer stack of transparent oxide materials of precise thicknesses on transparent quartz or mica particles. The resulting material then exhibits thin film interference and displays selective transmission of light. The spectral response can be engineered by appropriate choice of coating oxides, their thicknesses and order of deposition. A variety of transmission and reflection profiles can be obtained when this kind of interference pigment is incorporated in transparent media such as glass, optically clear plastic or various synthetic lacquers. Several families of interference pigments for applications ranging from printing inks to car paints and decorative coatings are commercially available from various manufacturers. Merck produces perhaps the best known family of such pigments under its offering of special effect pigments. One of the sub-family called Solarflair has been specially developed for solar heat protection applications in high solar potential regions of earth. Translucent plastic sheets containing Solarflair, for instance, serve as effective material for the construction of green houses and sky lights in tropical and subtropical countries. These pigments have been designed such that their dispersions allow a large fraction of shorter wavelength visible radiation to pass through but longer wavelength heat-producing infrared radiation is very effectively attenuated through reflection. The result is cool green houses and other enclosed ambients. Our work has investigated the use of transparent filters containing Solarflair pigments for use in shielding solar cells from infrared radiation while letting most of the visible light through for photovoltaic generation to take place. Our experiments have involved work on preparing both plastic-based and glass-based filter films containing Solarflair that could be directly deposited on the top surface of solar cells.

3. Solarflair and Coatings Incorporating Solarflair

Solarflair, also known as Iriodin, is a multilayer synthetic pigment consisting of basal mica coated with silicon dioxide (SiO_2), titanium dioxide (TiO_2) and tin oxide (SnO_2) overlayers. Weather resistant grades are also available that contain an additional coating of zirconium dioxide (ZrO_2). This pigment is temperature stable up to 800 °C. The two main commercial offerings from Merck are called Solarflair 870 and Solarflair 875. These pigments have particle sizes in the range of 10-60 μm and 5-25 μm respectively. The former is suitable for general purpose infrared blocking applications while the later is tailored to have a transmission spectrum that matches photosynthesis requirements of vegetation quite closely. Figure 1 shows a plot of the transmission and reflection spectra of Solarflair x in the wavelength range from x nm to y nm.

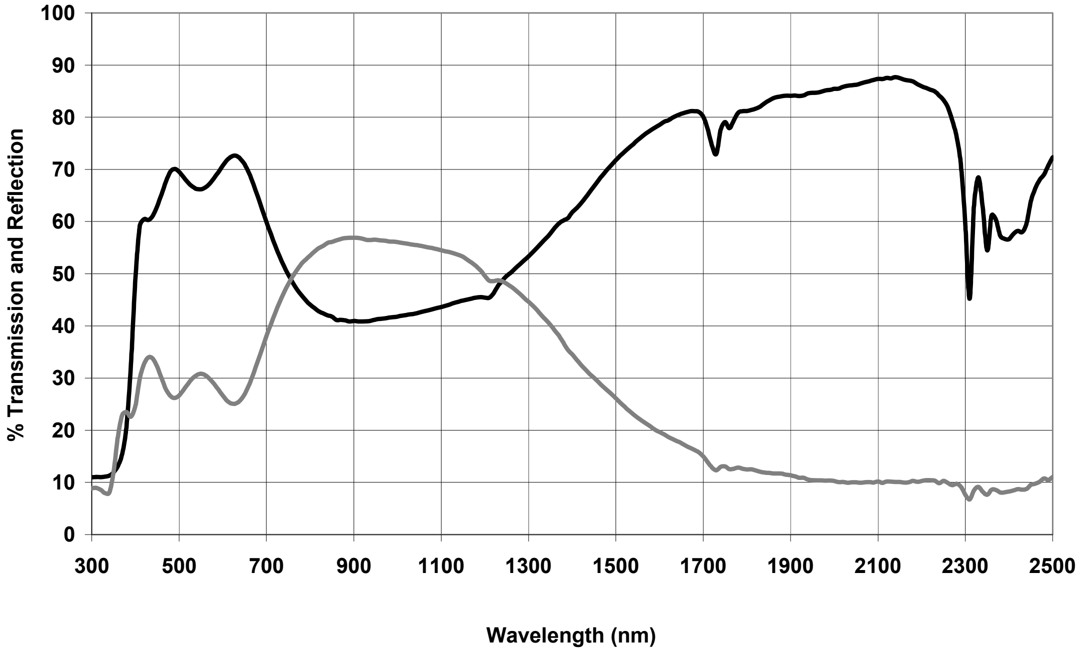

Figure 1. Spectral transmission and reflection of Solarflair 870 pigment particles

The actual pigments are inert, non-toxic, off-white powders that can be blended in plastics and glasses in various concentrations. It is possible to prepare a blend of Solarflair-containing acrylic plastic by mixing a desired amount of Solarflair in a solution of polymethyl methacrylate (PMMA) in a suitable solvent such as xylene or ethyl lactate. The loaded PMMA solution can then be coated on suitable substrates by any of a variety of coating techniques such as spray coating, roller coating or spin coating. With increasing Solarflair concentration the resulting films become less and less transmissive. An appropriate balance has to be struck with the Solarflair concentration such that as much infrared radiation as possible could be reflected away while attenuating as little as possible of visible light. With Solarflair itself is stable at temperatures in excess of 800 ºC, PMMA films containing Solarflair cannot withstand temperatures much above 100 ºC as the glass transition temperature of PMMA is only around 124 ºC. PMMA coatings also get scratched easily. Thus PMMA-based Solarflair coatings will clearly be unsuitable for use with solar cells exposed to aggressive outdoor environment. We, therefore, chose to work with silica-based coatings prepared from spin-on glass (SOG) precursors. Specifically, we used Intermediate Coating IC1-200 from Futurrex as the un-doped SOG. This is a polysiloxane-based polymer in n-butanol solvent. In usual application, it is spin coated at typically 4000 RPM on to cleaned substrates and then baked at 90 °C to remove any remaining solvent. A further anneal at 400 °C then converts it into silica. The resulting coating is tough and weather resistant. We investigated both PMMA and SOG coatings containing 10%, 15% and 20% by weight of Solarflair.

The transmission spectrum of each of these was measured and it was determined that SOG coatings containing 15% by weight of Solarflair, spun at 4000 RPM, were the most suitable for further experiments. However, it was also found that a 4-period stack of 5% Solarflair in SOG followed by un-doped SOG was even more suitable as it exhibited the largest contrast between the short wavelength pass-band and the long wavelength stop-band. A figure showing the transmission characteristics of these two types of films appears here as figure 2. Another feature that is seen here is the existence of a dip in transmission around 530 nm (green region) with single layer films. Such films have a distinct green hue in reflection. Multilayer films don’t show such a dip and have a very flat pass-band.

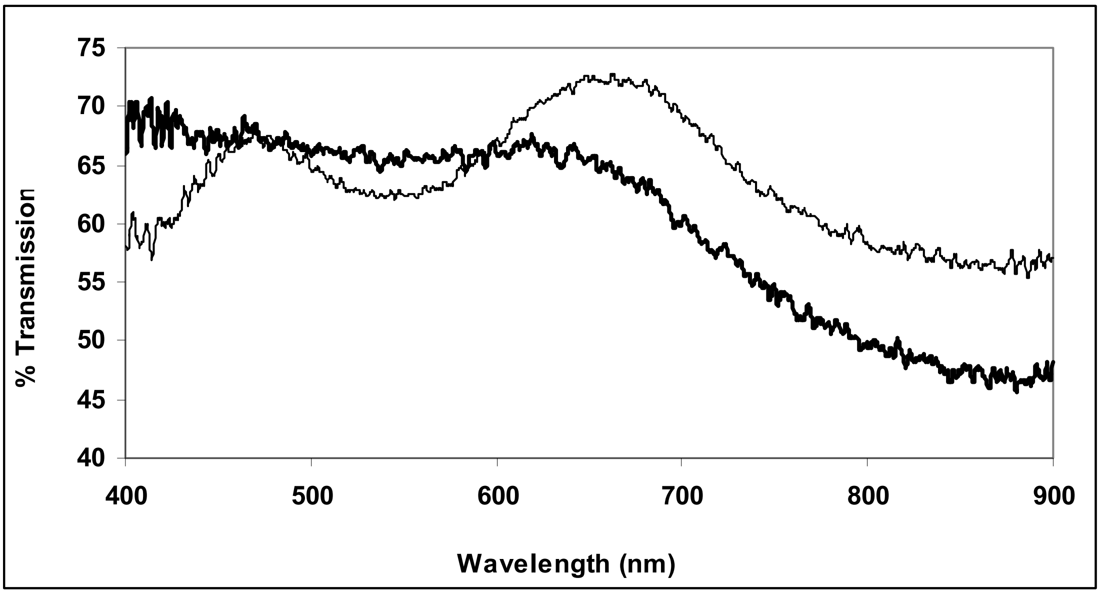

Figure 2. Spectral transmission of single layer (light curve) and 4-layer (bold curve) silica films containing 15% by weight of Solarflair

It is clearly seen from this figure that the multi-layer stack, though more laborious to deposit, was a better contender for infrared shielding applications. It features a relatively flat pass-band performance and a pronounced fall in transmission for longer wavelengths. However, the transition point – about 650 nm for the multi-layer coating – needs to move further towards the long wavelength side of the spectrum in order to better match with most inorganic solar cell materials. A shift of 100 nm would be very desirable.

4. Measurements on Solarflair-coated Solar Cells

We performed experiments on both GaAs and Si solar cells coated with Solarflair pigment embedded in SOG silica films. GaAs solar cells were fabricated from epitaxial structures grown at the University of Glasgow whereas amorphous silicon solar cells were purchased from Sanyo Corporation. The GaAs cells had a silicon nitride anti-reflection coating at the top whereas the Si cells were formed on 1 mm thick glass substrates. In both cases, Solarflair-containing SOG films were deposited and post-processed on solar cells through spinning from a butanol-based solution. A typical GaAs solar cell used in the experiments appears here in figure 3. The overlying Solarflair-containing silica films were only slightly translucent so they allowed a large amount of light to pass through to the cell.

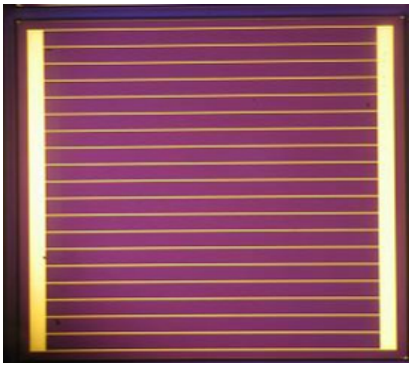

Figure 3. Epitaxial GaAs solar cell used in experiments

The optical responsivities of coated and uncoated cells were measured by illuminating them with a calibrated tungsten-halogen lamp as a light source[4]. The radiation contained both visible light and infrared radiation, as determined by a visible-infrared spectrometer. Open circuit terminal voltages (V_{OC}) were measured and plotted against incident optical power. Data was taken after the cells had stabilised in temperature. These results appear here in figure 4. The V_{OC} for coated cells was consistently measured to be about 0.5 volt higher than that for uncoated cells. This was also corroborated by the higher cell temperature measured for un-coated cells as compared to that for coated cells. Cells carrying a coating of Solarflair measured approximately 35 ºC lower in temperature than cells without the coating.

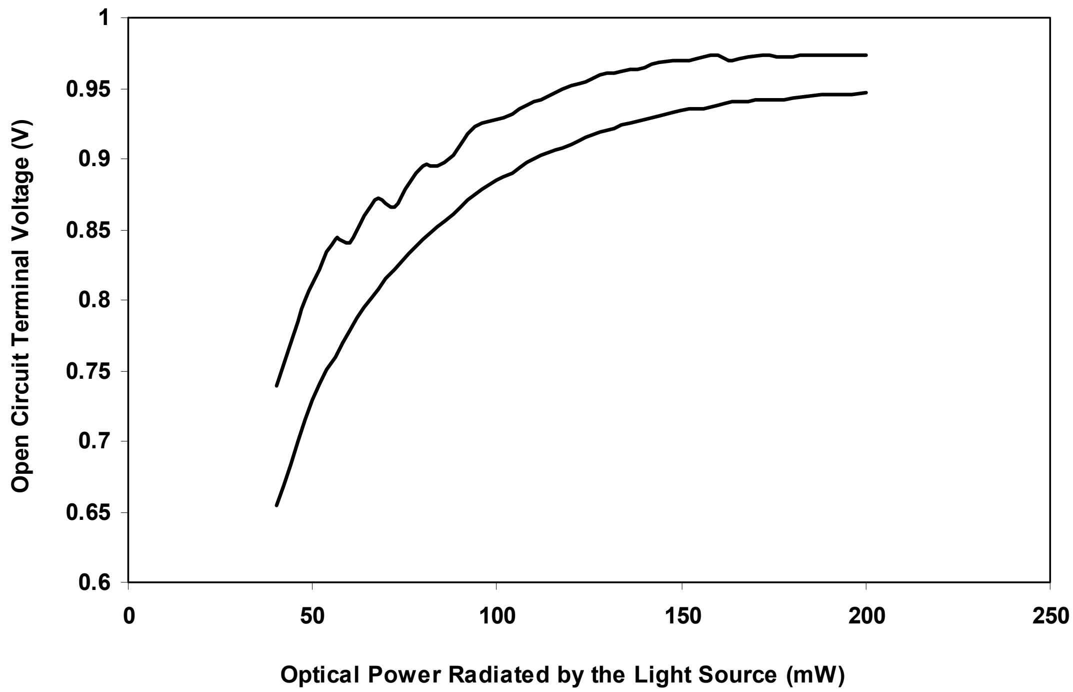

Figure 4. Responsivity curve showing open circuit terminal voltage as a function of illumination power for coated GaAs cells (top) and similar but uncoated cells (bottom)

This is clear evidence of the efficacy of Solarflair-based coatings in reducing photovoltaic cell temperature and raising their output voltage under radiant heating conditions.

The origin of the wavy structure in the optical responsivity of coated cells is not entirely clear but it is possibly due to interference effects in the Solarflair-loaded thin silica film. Silicon solar cells yielded similar results but showed even higher improvement in V_{OC}. Interestingly, the power output of silicon cells was seen to increase even under room light conditions once the cells were coated with Solarflair. It appears that the scattering of light by Solarflair particles enables better utilisation of light by these cells through a process of light trapping and results in the cells delivering higher electrical power output. This observation is very interesting because it suggests that by coating ordinary low performance solar cells intended for indoor applications in household gadgets it should be possible to obtain higher electrical power.

The effect of Solarflair films in shielding silicon photovoltaic cells from infrared radiation and thus maintaining them at lower temperatures compared to uncoated cells is seen in figure 5 where plats of temperatures reached by silicon cells under bright combined light-infrared radiation have been plotted as a function of time. The temperature of a reference uncoated cell is seen to climb to values at least 10 °C higher than that of coated cells. In high flux environments such as the interior of desert areas the ability of Solarflair coatings to keep photovoltaic cells cool and their efficiency high will evidently be of great value.

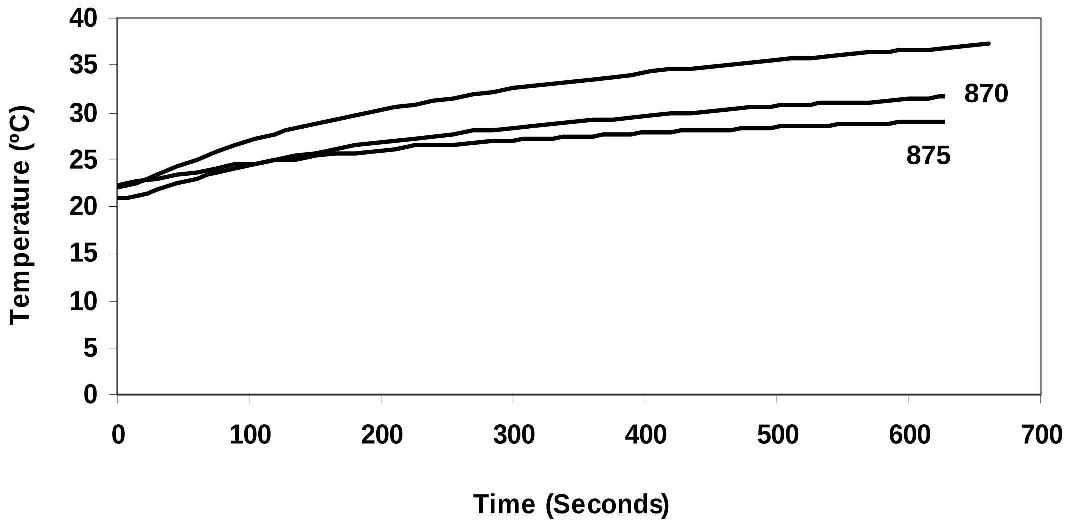

Figure 5. Plots showing temperatures reached by uncoated amorphous Si cell (top) and Solarflair-coated cells (bottom) as a function of elapsed time. 870 and 875 refer to two different versions of Solarflair.

5. Conclusions

Results of our experiments reported here show unambiguously that coating photovoltaic cells with silica films containing Solarflair pigments is very effective in keeping their temperatures down and thus enhancing their conversion efficiency in high flux environments. This results in higher open circuit terminal voltage and closed circuit cell current which lead to increased photovoltaic power output. Furthermore, the effect of light scattering and trapping leads to effective recycling of photons and that improves the functionality of even cells intended for room temperature operation.

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