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Mid-infrared emissivity of crystalline silicon solar cells

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ABSTRACT

The thermal emissivity of crystalline silicon photovoltaic (PV) solar cells plays a role in determining the operating temperature of a solar cell. To elucidate the physical origin of thermal emissivity, we have made an experimental measurement of the full radiative spectrum of the crystalline silicon (c-Si) solar cell, which includes both absorption in the ultraviolet to near-infrared range and emission in the mid-infrared. Using optical modelling, we have identified the origin of radiative emissivity in both encapsulated and unencapsulated solar cells. We find that both encapsulated and unencapsulated c-Si solar cells are good radiative emitters but achieve this through different effects. The emissivity of an unencapsulated c-Si solar cell is determined to be 75% in the MIR range, and is dominated by free-carrier emission in the highly doped emitter and back surface field layers; both effects are greatly augmented through the enhanced optical outcoupling arising from the front surface texture. An encapsulated glass-covered cell has an average emissivity around 90% on the MIR, and dips to 70% at 10 µm and is dominated by the emissivity of the cover glass. These findings serve to illustrate the opportunity for optimising the emissivity of c-Si based collectors, either in conventional c-Si PV modules where high emissivity and low-temperature operation is desirable, or in hybrid PV-thermal collectors where low emissivity enables a higher thermal output to be achieved.

1. Introduction

Improving the energy yield of photovoltaic (PV) solar cells is of ongoing concern. Of the many types of PV solar cell that have been developed, the crystalline silicon (c-Si) cell is by far the most commercially successful, though by no means the most efficient. This is a technology that is reaching its fundamental efficiency limits, and whose efficiency has plateaued over many years: a world record of 26.3% was announced in 2017 [1], to be compared to 24.4% in 1998 [2]. In this context, the scope for this technology to undergo significant further efficiency gains under standard test conditions (STC) is limited.

Despite their plateauing efficiency at STC, there remains an opportunity to improve the power output of c-Si solar cells under real operating conditions. The efficiency of most PV cells decreases linearly with increasing temperature, the so-called temperature coefficient of today's commercial c-Si based cells being between 0.28–0.52%/°C [3]. Whereas the STC temperature is 25 °C, cells in the field typically operate closer to 50 °C [4]. Assuming a rated efficiency of 25% at STC, this implies an efficiency drop of nearly 3% points.

Operating temperatures can be reduced by either passive or active cooling. Passive cooling is achieved by transmitting heat by radiation, natural convection and conduction, from the generation zone to the dissipation area [5,6], while active cooling systems transfer heat either to a tube that flows at the cell back contact [7] or the cell is directly immersed in a dielectric fluid that extracts the heat [8]. Hence, active systems consume energy to obtain higher cooling capabilities. These are all costly or bulky systems, hard to implement in large scale PV deployment without a significant increase in the cost of energy. More recently, it has been proposed that solar cells can be cooled radiatively via so-called emissivity control [9,10]. Introducing an array of silica pyramids onto the cover glass changes the emission spectrum maximising thermal emission through the atmospheric transmission window into the cold space beyond the atmosphere, while preserving the solar absorption properties [9]. This is a particularly attractive means of improving the operating efficiency due to its evolutionary nature: emissivity control measures can be added to an existing cell or module and so their fabrication does not disrupt processing chains that have already achieved economies of scale. What's more, radiative

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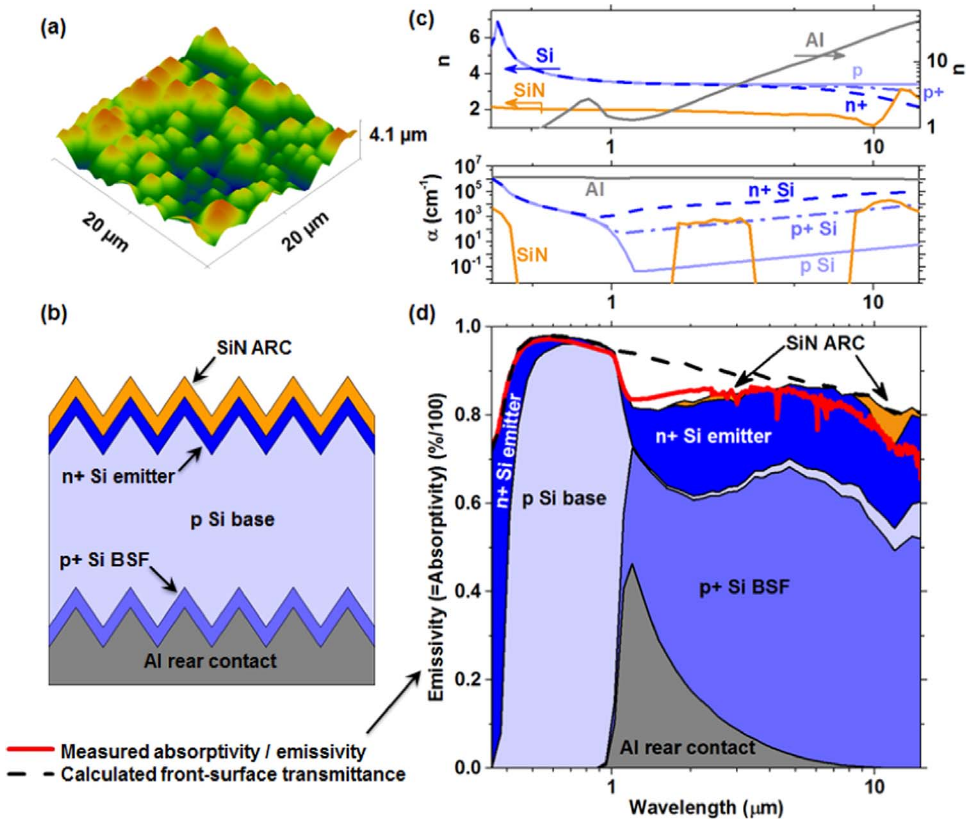

Fig. 1. Model details and results together with experimental findings. (a) Atomic force microscopy (AFM) micrograph of the front texture of the c-Si cell under investigation. (b) Cross section schematic of the modelled solar cell structure (not drawn to scale). (c) Optical constants used in the model. (d) Measured (red line) and modelled (total filled area) emissivity/absorptivity of c-Si solar cells. The individual filled areas show the contribution of each layer to the emissivity/absorptivity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

cooling is seen as an increasingly encouraging approach following the landmark achievement of passive radiative cooling of a body (not a PV cell) below ambient air temperature under direct sunlight [11].

In another application, there also exists the motivation to do the opposite and suppress the thermal emission of PV cells and modules. Specifically, in hybrid photovoltaic-thermal (PV-T) systems the thermal efficiency can be improved using spectrally-selective low-emissivity coatings to reduce radiative thermal losses [12,13]. Indium tin oxide (ITO) or aluminium-doped zinc oxide (AZO) films deposited by sputtering have been used as low-emissivity coatings, since they are highly reflective in the mid-infrared [14].

The radiative emissivity of PV cells is therefore gaining increasing interest in the community. However, despite being a fundamental property of the solar cell, very little is known about the emissivity of real devices and its physical origins. Sopori et al. modelled the emissivity of polished and textured silicon wafers in the 0.5–10 µm range, with and without a thick (1 µm) dielectric coating as a function of doping and temperature [15,16]. However, these structures are far from real solar cells, in that they are uniformly doped and have texturing on only one side. Santbergen and van Zolingen studied numerically and experimentally the absorptivity, which is equal to the disperse emissivity via the Kirchoff relation, of PV cells up to 1.7 µm, reporting a 90% absorption of the AM1.5 spectrum in this range and the contribution of each layer of the structure [17]. Recently, the emissivity of silicon solar cells up to 25 µm was considered to be equal to the emissivity of a planar p-doped silicon wafer [9,10]. This wafer is similar to the typical base region on commercial silicon cells. However, this assumption does not consider the impact of the texture and the highly doped regions, which are shown in the present work to dominate the emissivity of an unencapsulated c-Si solar cell.

In this paper, the emissivity of presently-manufactured silicon solar cells has been measured in the 0.35–16 µm range, and the first full radiative model of a solar cell considering both absorption in the spectral range of sunlight and thermal emission in the mid-infrared (MIR) has been developed. The model considers the complete cell structure with realistic layer properties and front and back textures. We demonstrate that a c-Si solar cell is highly emissive in the MIR, and that this is mostly due to the highly doped, but very thin, emitter and back-surface field layers. These highly doped layers have been overlooked in previous MIR emissivity studies, although their contribution to NIR absorption was recognised by Santbergen and van Zolingen [17]. We also provide a discussion of how light trapping/outcoupling contributes to emissivity and in which spectral regions, and investigate how changes to device parameters such as doping levels and texture angle may affect the emissivity. This is important since parameter changes in future PV-cell designs may have unintended effects on the emissivity, or the cell design may be intentionally changed in order to control emissivity. The model is then used to predict the emissivity of an encapsulated PV cell under soda-lime-silica low-iron glass, from which we deduce that the MIR emissivity of a PV module is also very high and almost independent of the underlying solar cell structure. The presented study serves to underpin ongoing research into emissivity control, and to better understand a basic property of the c-Si solar cell, which is becoming one of the world's most ubiquitous optoelectronic devices.

2. Methods

Absorptivity/emissivity measurements were performed on commercially available monocrystalline c-Si solar cells, purchased from Bolisheng Technology [18], which are considered to be representative of most commercially produced aluminium-back-surface-field (Al-BSF) c-Si solar cells. The topology of the surface texture was measured with a WITec Alpha 300RS atomic force microscopy (AFM) system. This confirmed a texture of randomly sized pyramids with an elevation angle close to 55°, which is known to be typical of industrially produced c-Si solar cells [19]. An AFM micrograph is shown in Fig. 1(a), demonstrating pyramid sizes on the order of 2 µm in height. It was confirmed