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Bionic micro porous evaporation foil for photovoltaic cell cooling

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ABSTRACT

A novel cooling system for photovoltaic (PV) cells on the basis of a bionic evaporation foil is demonstrated. A prototype version of the foil is presented which has been realized by a two-layered dry film resist. The foil is laminated directly on silicon substrates providing good thermal contact with the water cooled down by evaporation. In this work the fabrication of the evaporation foil is shown as well as the cooling capabilities with respect to environmental temperature, pore density, structure heights, etc. The bionic evaporation foil provides cooling performance equivalent to the state of the art of today's PV-systems. A temperature reduction up to 11.7 °C is proved with perspective to further significant enhancement. The presented system is capable of self-regulating the water flow and the resulting cooling rate by its direct dependency on environmental conditions like temperature and air velocity.

1. Introduction

Currently the increasing demand on green energy leads to a request of highly efficient working photovoltaic modules. In contrast, the electrical efficiency of commercial PV-cells in general is in the range of 12–15% while the illumination of sunlight heats the PV-Modules with 1.8 K/100 W/m^2 [1]. Increasing the module temperature leads to the decrease of photon penetrability and the reduction of the band gap [2,3]. The resulting rise of short circuit currents at almost constant open-circuit voltages results in a decreasing electrical efficiency of 0.13–0.5%/K [1,4]. Cooling the PV-Modules during the illumination periods is a reasonable method to increase the electrical power output. Typical principles are based on radiator chillers working with either air [1] or water [5,6] as coolant, compositions of PV-cells surrounded by cooling surfaces and louvers [4]. Heat pipes [7,8] are effective but bulky cooling mechanisms. For all these systems the required complex assemblies are inappropriate for PV-cells inline mass production. The only commercially established cooling mechanism is ventilation by air space. It achieves temperature decreases of 5–6 °C [9]. This research work presents an exceptional cooling mechanism for PV-modules inspired by nature's best refrigeration: the evaporation cooling.

The integrated bionic cooling system is imitating the water transport mechanism of trees, emulating plant's transpiration and human perspiration with a thin micro structured polymer foil by evaporating water through micro pores on the back side of PV-modules.

2. Principle and design concept

The human perspiration [10] is based on bulk water undergoing a phase transition to water vapor. For this transition water requires a huge amount of thermal energy which is extracted from the water and the surrounding system. To evaluate the expected cooling effect the temperature reduction ΔT can be calculated by:

$$\Delta T = \frac{h \cdot \Delta m}{c \cdot \rho \cdot V} \qquad (1)$$

where h describes the specific enthalpy, Δm the amount of evaporated water mass, c the heat capacity, ρ the density of water and V the water volume contained within the evaporation region [11]. This is a simplification disregarding the conductive and convective heat transfer.

For a highly efficient cooling foil also a self-driven water transport mechanism is required. Taking the nature as ideal one can adapt from trees not only the cooling mechanism but additionally the pumpless water transport which consists of capillary forces as well as evaporation. The biological realization of this fluidic system is capable to generate the transpiration pull [12]. The essential transpiration elements of a tree are the root as a water reservoir, the trunk containing channels for transporting water from the reservoir to the evaporation area and nano pores in the leaves [13,14]. The actual cooling takes place by evaporating water within these

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pores. While water is leaving the leaf a negative pressure [15] is building up in the system resulting in a self-driven water transportation which is operating only on the basis of solar radiation and can be considered therefore energy-autarkic.

The implementation of essential functionalities into the bionic evaporation foil for PV-cell cooling is shown in Fig. 1. The basis is a silicon substrate in microscope slide size representing the PV-cell (L1). On the back side a first layer of permanent dry film resist (L2) is applied containing the water transporting channels as well as circular spacers for a layer separation. An additional layer L3 of this resist on top builds the fluidic sealing and contains through-holes as water inlet for the connection to an external reservoir as well as micro pores representing the evaporation surface. The pore diameter has to be large enough to provide high evaporation ratios but adequately small to fill the pores by capillary forces. In accordance with formula (2) [16] the maximum pore diameter d is 35 μm aiming a future up scaling up to 0.15 m height of the water column in consideration of the surface tension σ with 0.074 N/m, contact angle α of the resists which has been investigated to be 80 ± 2° by sessile drop method using deionized water, water density ρ with 995.67 kg/m^3, gravitation acceleration g with 9.81 m/s^2 and capillary rise h with 0.15 m:

$$d = \frac{4 \cdot \sigma \cdot \cos(\alpha)}{\rho \cdot g \cdot h} \quad (2)$$

The relation between inlet and pore surface was chosen to 1:5 for practical reasons i.e. to keep the total system dimension as small as possible and ensure reasonable flow rates. The inlet region provides squared through-holes of 150 μm × 150 μm size and 100 μm pitch within a cylindrical water contact area of 40 mm diameter which represents the interface to the reservoir via sample holder.

3. Technical realization

The realized test chips use silicon of 25.5 mm × 76 mm × 525 μm size metalized with 20 nm chromium and 100 nm aluminum as substrate representing the PV-cell. The bionic evaporation foil consists of two identical layers epoxy based permanent dry film resist using either PER MX 3050 (DuPont) with 50 μm or TMMF S2030 (TOK) with 30 μm thickness and equal process parameters for both resists. The substrate is covered with permanent dry film resist utilizing hot roll lamination at 80 °C followed by removing the polyester-foil, 7 min at 115 °C post lamination bake on a hot plate and i-Line UV-exposure (MA-6, SüssMicroTec) with a dose of 255 mJ/cm^2. The chromium-glass-mask contains circular spacers of 70 μm diameter in the inlet (18 mm × 14 mm) and evaporation region (18 mm × 25.4 mm) connected by 76 channels of 100 μm width in the transport region (18 mm × 24 mm). After a relaxation period of 4 h and 8 min post exposure bake at 150 °C the development of the structures using 2-methoxy-1-methylethyl acetate (micro resist technology) completes this layer preparation. The sealing top layer L3 is laminated by a sacrificial layer [17] or by top-side-down lamination at 70 °C skipping post lamination bakes due to a glass transition temperature of 50 °C for both types of unexposed permanent dry film resist. For the L3 (50 μm thickness for PER MX, 30 μm thickness for TMMF) exposure a chromium-glass-mask containing squares for the inlet and circular pores of 32 μm diameter in the evaporation region is used. After exposure with a dose of 140 mJ/cm^2 and relaxation time a post exposure bake at 150 °C (top-side-down) and development complete the fabrication. Fig. 2 shows the final chip with the bionic evaporation foil and cross sections through pores of the evaporation area of both resist types where the spacers are clearly carrying L3 due to its isolation.

The final chips are mounted in a holder which is connecting the chip with the external reservoir featuring a small opening to ensure pressure compensation by negligible evaporation. On the back side of the chip in the middle of the evaporation region a Pt100 is thermally connected for resistive temperature measurement. Fig. 3 shows a chip in the holder connected with the reservoir and a schematic drawing of the interface as well. The holder interfaces the chip inlet (squares) by a circular water contact area via tubing with the reservoir while a gasket (black circle) provides sealing.

4. Experimental results and discussions

The test system and the deionized water is preheated in the test climate chamber for at least 16 h to ensure temperature equalization between climate chamber, sample, holder and water reservoir. Using deionized water fits the biological system best since water is always filtered by membranes before entrance. Additionally undesirable plugs due to e.g. calcification are excluded. The setup is filled by a syringe to the intersection between channels and pores. Within the next 15 min the pore region is completely self-filling due to capillary forces. The weight of the system including Pt100 and the related wires is measured before start and after end of

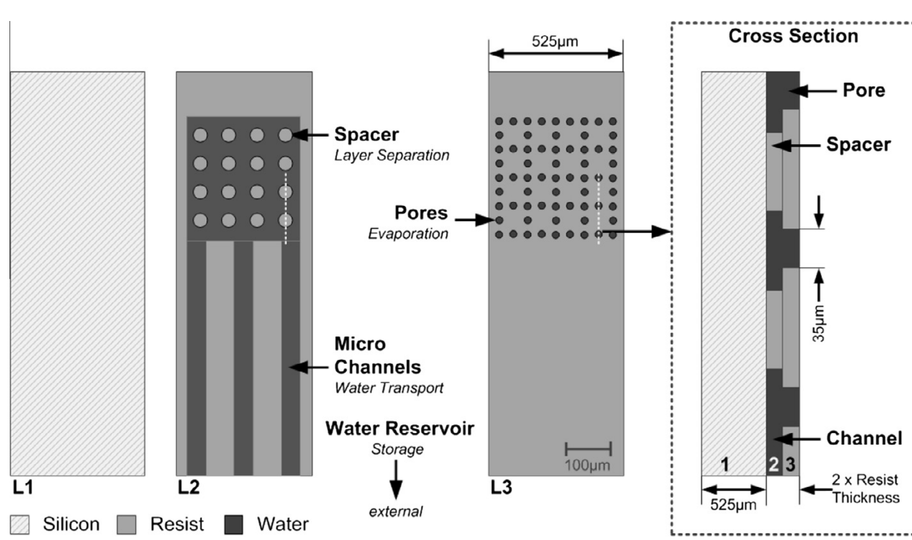

Fig. 1. Design for layer composition with related functionalities.