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ORIGINAL RESEARCH
PAPER

Integrated cooling solution for concentrator photovoltaic cells

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ABSTRACT

The efficiency of the most modern photovoltaic cells currently reaches 40–45%, which is achieved by concentrator systems. However, despite better device efficiencies concentrator photovoltaic cells have major drawback, namely the high amount of waste heat, which requires new cooling solutions.

This paper gives a short overview of the current cooling techniques and proposes a novel micro-channel cooling solution for concentrator photovoltaic cells. In the concept, the microscale channels are integrated into the backside metallization of the PV device. The paper gives a description of the technological process that can be used to produce microchannels on the back of solar cells and shows the optimization of the channels to achieve optimal cooling performance.

KEYWORDS

concentrator photovoltaic, microchannel, cooling, copper electroplating

1. INTRODUCTION

Concentrating the incoming light on the surface of solar cells is a promising way of enhancing the efficiency of photovoltaic devices. In fact, most of the efficiency records of recent years have been reached with Concentrator PhotoVoltaics (CPV) [1]. However, despite better device efficiencies CPV systems have a major drawback, namely the high amount of waste heat that is caused by the high-power density and the photovoltaic conversion losses.

1.1. CPV systems

On the contrary to conventional photovoltaic systems, concentrator photovoltaics use large surface concentrators, which are lenses and/or curved mirrors, to focus sunlight onto small, but highly efficient, multi-junction solar cells [2]. Depending on the level of concentration it can be distinguished low and high-level concentration devices [3]. Even by using today's best available solar cells types with efficiencies between 40 and 46% [4], at light concentration level of 1,000 suns the heating power is over 50 W/cm². At these power densities, the efficiency of the device is greatly reduced due to the increased temperature of the solar cell. Thus, efficient cooling of CPV devices is unavoidable.

2. COOLING SOLUTIONS FOR CONCENTRATOR PHOTOVOLTAICS

Demonstrating the importance of the topic, numerous studies have been conducted in recent years. There are many works in the literature that summarize the technologies used to cool concentrator solar cells well [5–8]. These devices can be divided into two main groups based on their operating principle.

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2.1. Passive cooling methods

The first group is passive cooling solutions, which can be used to cool cells without the need for additional energy.

The most common solutions are operating with the natural convection of the air. The cooling effect – same, as at the conventional free-standing PhotoVoltaics (PV) modules – is usually the wind and the buoyancy driven flows [9]. Its simplest design is a simple heat spreader made of aluminum [10] or copper [11]. With these devices, the cooling efficiency can be influenced by the surface and thickness of the distributor. More sophisticated tools are finned heat sinks [12], where fins serve to increase the surface of the heat transfer. Aldossary et al. [13] investigated the difference between round pins - and straight fins heat sink. Micheli et al. [14] examined the cooling efficiency of a micro finned silicon heatsink structure.

In addition to devices with natural convection, heatpipe-based cooling devices [15] are also used for passive cooling of CPVs. In heatpipes, heat transfer is based on the phase transition of the working fluid inside it [16]. Cheknane et al. [17] compared water and acetone as the working fluid, in a gravity-dependent copper heat pipe.

In passive cooling technologies, cooling performance is limited and highly dependent on the ambient temperature and air velocity. As a result, they are no longer effective enough above certain concentrations, so active cooling is required.

2.2. Active cooling methods

Active cooling solutions are more effective than passive cooling solutions. The only disadvantage of these techniques is that they require extra energy to pump the refrigerant material, which is mostly air or water.

As with passive cooling solutions, the simplest tool among active solutions is cooling a finned heatsink with forced air convection. Soliman et al. [18] investigated experimentally a finned heat sink cooling system with forced convection, compared with only natural convection. The other simple application of single phase forced convection is to circulate cold water in rectangular tubes under the solar cell [19]. Due to the higher convection coefficient and thermal capacity, water cooling offers better performance than air cooling. Therefore, it is more suitable as a working fluid of heat exchanger [6].

Improving water-cooled channels can increase cooling performance. Tan et al. [20] investigated multiple-channel heatsink, to increase the surface area. Another improved channel type includes metal foam in the channels. Metal foam has a high surface area per unit volume, thermal conductivity and tortuous flow path to promote mixing is an ideal candidate for thermal management applications [21].

Another cooling solution is direct liquid-immersion cooling; bare CPV solar cells are immersed in a circulating liquid. Thus the contact thermal resistance between the solar cell and the cooling system is minimized or eliminated, and heat is taken away from both the front and rear cell surfaces [22]. A narrow rectangular channel receiver using a

dimethyl silicone oil immersion cooling method was designed for a linear CPV system and its performance was investigated experimentally [23]. Kang et al. proposed a cooling method for temperature control of dense-array solar cells with direct-contact phase-change liquid immersion cooling method [24].

One of the most efficient cooling methods is liquid jet impingement [25]. A high velocity liquid is forced through a narrow hole or slot into the surrounding air, and onto a surface to be cooled. The impinging jets can extract a large amount of heat because of the very thin thermal boundary layer under the impingement [1]. Royne suggested a device that contains a matrix of nozzles [26] and Bahaidarah [27] stated that the advantage of using impingement cooling can result in low average cell temperature for PV cell with uniform temperature distribution across series connection.

By using a refrigerant other than water, the phase transition of the liquid coolant can be utilized as two-phased forced convection cooling. By allowing the coolant fluid to boil, the latent heat capacity of the fluid can accommodate a significantly larger heat flux [5]. For two-phase flow, the working fluid's saturation temperature had the greatest effect on the cell temperature and efficiency [28]. Reeser et al. [29] investigates the potential application of two-phase micro-cooler for thermal management of a concentrated photovoltaic cell illuminated with 2000 suns and cooled with flow boiling of R134a [30] refrigerant material.

Among the great number of cooling solutions, one of the best cooling performances was achieved with micro-channel heat sinks. For a heat sink of $1 \times 1 \text{ cm}^2$, the lowest reported thermal resistance is $9 \times 10^{-6} \text{ K m}^2/\text{W}$ [31]. The study of Radwan showed that the microchannel cooling technique achieves the lowest solar cell temperature in comparison to other cooling methods [32]. The main idea is that the convective heat transfer coefficient scales inversely with the flow characteristic dimension. Consequently, a significant reduction in the thermal resistance can be achieved with the use of microchannel cooling system [5]. The key problem of water-cooled microchannel cooler system design is to ensure that the surface of the solar cells and the heat exchanger has good thermal conductivity and electrical insulation [6].

Reference [33] provides a comprehensive review of various methods reported in the literature and discusses various design and operating parameters influencing the cooling capacity for PV systems leading to an enhanced performance.

Enhanced microchannel devices employ a number of solutions, for example specific hybrid jet impingement/microchannel cooling scheme [34]. Radwan et al. [35] developed a new cooling technique by using a microchannel heat sink with nanofluids. Nanofluids as Aluminum Oxide (Al_2O_3) – water and Silicon Carbide (SiC) – water, in comparison with pure water are used as cooling mediums. In the study [36], laminar forced convection heat transfer of Al_2O_3 and TiO_2 nanoparticles-based water nanofluids inside a vertical tube was numerically studied. The results of this work indicate that the use of Al_2O_3 /water and TiO_2 /water

nanofluids in a pipe can increase the heat transfer performance. The performance of the microchannel heatsink can be further enhanced by the use of a multi-layer manifold microchannel cooling system. The device can effectively lower the surface temperature, improve surface temperature distribution, reduce the pressure drop, and increase the heat transfer coefficient, resulting in a lower pumping power and a higher net output power of CPV cells [37].

A good overview of cooling solutions for CPV devices can be found in [38], in terms of micro- and nanotechnologies. Using microchannels for the cooling of CPV devices has been discussed in several studies and can be mainly divided into two groups.

- Solutions where the microchannels are directly incorporated into the semiconductor bulk material of the PV device (a good overview of these type devices can be found in [37]);
- Devices where the micro-cooler is attached on the back surface of the PV device [39, 40].

Although the first group of solutions gives the lowest thermal resistance, there are several drawbacks: Microchannels are incorporated into the bulk semiconductor by costly microtechnological processes. The light absorption volume and mechanical stability are decreased. Moreover, it can be used mainly for single crystal silicon solar cells only. The second class of solutions has no drawbacks regarding the mechanical stability and semiconductor material restrictions, but the necessary Thermal Interface Material (TIM) [41] between the micro-cooler and the PV-device increases the thermal resistance of the cooling system, and the ageing of the TIM can also be an issue over time.

In this approach, an incorporation the microchannels into the backside metal contact layer is suggested, this way most of the drawbacks of the upper mentioned solutions can be eliminated: this way we have no restrictions in semiconductor material, no decrease of mechanical stability and the thermal resistance of the TIM can be eliminated.

3. METHODS AND MATERIALS

The proposed cooling solution is formed by electro-plating copper on the backside of any type of solar cell structure. In this approach, the micro-cooler serves also as the back-contact metallization, thus no additional metallization is needed, and the back contact is made of a well conducting and cheap material. In this paper an improved fabrication method will be presented to produce the microchannels in the backside contact metallization.

3.1. Introduction of the improved process

In previous approaches the differing lateral and vertical growth speeds resulted in a very thick cover layer over the microchannels [42]. This uneven growth and thus the thickness of the cover layer can be reduced by adding

an additional intermediate seed layer and lithography patterning to the process steps. The preliminary version of this process was presented in our earlier work [43]. The improved process steps, indicating the layers created, are depicted in Fig. 1.

As a first step, an approximately 80 nm thick titanium layer is evaporated on the back surface of the solar cell, which serves as adhesion and (during a possible subsequent heat treatment) a barrier layer. In the same vacuum step, an approximately 130 nm thick copper layer is evaporated onto the titanium layer; this is the seed layer for the electroplated copper layer that contains the microchannels. After this, a thick negative photoresist (approx. 70 μm thick) is coated onto the copper seed layer, which is followed by the exposure of the channel pattern and the photoresist development.

Fig. 1. Process steps for the fabrication of the microchannels: 1) Processed solar cell with front contacts and no back contact; 2) Stacked evaporation of a titanium adhesion layer and a copper seed layer; 3) Application of channel pattern from a thick negative resist; 4) Copper layer growth around the photoresist channel pattern by electroplating; 5) Evaporation of the intermediate copper seed layer; 6) Etching of the copper layer with a second lithography process; 7) When the channel width is reduced to 10–20 μm , the resist is stripped from the surface; 8) Electroplating continues until the channel is closed

Thus, photoresist covers the parts where the channels are going to be formed, and the electroplated copper will only be able to grow on the uncovered parts of the seed layer. After the copper has reached the thickness of the photoresist layer, a new approximately 140 nm thick copper is evaporated as an intermediate seed layer. After a second lithography step, the seed layer is etched away above the channel pattern in a width of 60 μm and the plating is continued. When the residual channel width reaches 10 μm and the plated copper on the second seed layer has an appropriate mechanical stability, the photoresist is removed, and electroplating is proceeded. The electroplated layer grows on the outer surface of the copper due to the surface potential. Because of this, there is no significant reduction on the inner walls of the channels. This way the copper layer grows together and closes the top of the microchannels.

3.2. Mask designing and geometries

The test structure is a cooling device for a concentrator solar cell with a size of $20 \times 20 \text{ mm}^2$, where channel geometries are optimized for an even distribution over the solar cell area. Microchannel layout is shown in Fig. 2.

The layout contains 55 channels which are 200 μm wide each. The distance between the centerlines of the channels is 300 μm . The effective length of the channels is 6 mm which were optimized with thermal simulations [44]. Each channel has an inlet at the center line of the cell and two outlet openings on the edges that are suitable to circulate liquid coolant. The width of the inlet/outlet is 1.5 mm. The technological distance on the sides of the CPV module is around 2.5 mm. In this area microscale channels cannot be formed.

In the previous works however the channel geometry often deformed during resist removal and the subsequent electroplating, resulting in a lower cross section, reduced flow and higher thermal resistance. Due to this the technological step line must be optimized for the proposed process. For this the geometry of the second mask that is used during the second seed layer patterning was modified. Instead of the former straight opening, a dashed pattern with $60 \times 60 \mu\text{m}$ rectangles, a raster feature of 100 μm is provided as it can be seen in Fig. 3, so that the non-etched copper layer serves as a bridge and provides mechanical stability to the second seed

Fig. 2. The mask pattern of the microchannels

Fig. 3. The mask for second seed layer patterning, with the dashed lines

layer, above the thick photoresist. As the height of the channels is 70 μm , with this raster size, it is ensured to remove the lacquer in the section between the two open points during the isotropic resist removal process.

3.3. Electroplating and technology optimization

For achieving the most uniform electroplated surface, a current density of 20 mA/cm^2 is the most optimal based on experimental values [45]. Based on preliminary experiments, relatively large crystal particles are formed on the plated surface. Crystal grains can be up to 40 μm in diameter. This is disadvantageous for the planned process, since if this bigger chunks are formed at the closing edge, it is not possible to exactly determine the point of time, when the gap is reduced to 10–20 μm (step 7), when the resist should be removed from the channels. In addition, the gap gets very uneven. To eliminate the inhomogeneous growth rate along the channels, and to achieve a more even copper surface, leveler additive was introduced to the electroplating bath. Based on solutions found in the literature [46, 47], Janus Green [48] powder-based leveling agent was used. Furthermore, the galvanic bath did not properly wet the photoresist, resulting in defects in the corners of the patterns due to trapped air bubbles, which masked the surface during galvanization. To solve this, 50 ppm Sodium Chloride was added to the solution as chloride ions behave as a surfactant in the solution [49]. The resulting copper layer is much more uniform and consists of 3–4 μm small crystals and growths with a rate of 32 $\mu\text{m/h}$.

4. RESULTS

Using the presented process, a structure was created containing electroplated microchannels on a stacked layer of titanium and copper as back-contact metallization of the silicon-based solar cell. Optical microscopy was carried out to investigate the geometry of the channels before the evaporation of the second seed layer. In Fig. 4 the patterns of 200 μm wide and 70 μm high channels and the corners can be seen, before and after the surfactant was added to the plating solution.

Fig. 4. Defects in the corners of the patterns due to trapped air bubbles (left) and the fault-free channel patterns after application of surfactant (right)

The overall process time was reduced by 4 h, from 12 to 8 h, compared to the first non-improved technology. After improving the process with the new second intermediate seed layer patterning, the process time decreases more, because after the second copper layer had been etched, due to the dotted pattern, the surface to be galvanized remained larger over the channels and had more edges for lateral growth.

5. CONCLUSION

In this paper a short overview of the current cooling techniques for CPV was given and a concept for the back side contact integrated cooling solution for concentrator photovoltaic cells was presented. The concept has the advantage that it can be universally applied to a wide variety of solar cells, does not weaken the solar cell mechanically, but keeps the thermal resistance at the possible minimum. The paper also presented an improved process for the fabrication of this microscale channel cooling network. The 200 μm wide and 70 μm high channels were formed by electroplating around a thick photoresist. Optimizing the plating bath, a solution was found for corner defects. Introducing a new intermediate seed layer into the technology process line, the channel closure is faster, and with the patterning of the dashed lines, no major reduction in cross-section occurs after the photoresist is removed.

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