

Conference materials

UDC 53.04

DOI: <https://doi.org/10.18721/JPM.183.248>

Thermal management of solar cells through down-conversion nanoparticles

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Abstract. Silicon-based solar cells are currently the most widely used, accounting for 90.9% of the global photovoltaic module production. Solar radiation in the wavelength range of 400 to 1200 nm is effectively absorbed by crystalline silicon solar cells and converted into electrical energy, and the remaining energy is converted into thermal energy. The efficiency of silicon-based solar cells is very sensitive to temperature. For every 1 °C increase in the temperature of the photovoltaic panel, the efficiency will decrease by 0.5–0.65%. Down-conversion nanoparticles can convert ultraviolet rays into visible light that is easy for photovoltaic panels to absorb. This paper first established a thermodynamic model for coating titanium dioxide nanoparticles with a grain size of 20 nm on the surface of crystalline silicon solar panels and experimentally confirmed that this method can effectively reduce the operating temperature of silicon-based photovoltaic panels while ensuring electrical performance.

Keywords: crystalline silicon solar cells, down-conversion, nanoparticles, reduction of solar cell temperature

Funding: The work was partially supported by the CSC (China Scholarship Council) scholarship program (project No. 202409010253).

Citation: Bi J., Pang H., Eidelman B.L., Thermal management of solar cells through down-conversion nanoparticles, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 18 (3.2) (2025) 237–241. DOI: <https://doi.org/10.18721/JPM.183.248>

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Материалы конференции

УДК 53.04

DOI: <https://doi.org/10.18721/JPM.183.248>

Терморегулирование солнечных элементов с помощью наночастиц даун-конверсии

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Аннотация. Кремниевые солнечные элементы в настоящее время наиболее широко распространены, составляя 90,9% мирового производства фотоэлектрических модулей. Солнечное излучение в диапазоне длин волн 1200–400 нм эффективно поглощается кристаллическими кремниевыми солнечными элементами и преобразуется в электрическую энергию, тогда как оставшаяся энергия превращается в тепловую. Эффективность кремниевых солнечных элементов крайне чувствительна к температуре. При повышении температуры фотоэлектрической панели на каждый 1 °C эффективность снижается на 0,5–0,65%. Наночастицы даун-конверсии способны преобразовывать ультрафиолетовые лучи в видимый свет, легко поглощаемый фотоэлектрическими панелями. В данной работе впервые разработана термодинамическая модель нанесения наночастиц диоксида титана размером 20 нм на поверхность кристаллических кремниевых солнечных панелей, а также экспериментально подтверждено, что данный метод эффективно снижает рабочую температуру кремниевых фотоэлектрических панелей при сохранении их электротехнических характеристик.

Ключевые слова: кристаллические кремниевые солнечные элементы, даун-конверсия, наночастицы, снижение температуры солнечных элементов

Финансирование: Работа выполнена при частичной поддержке стипендиальной программы CSC (China Scholarship Council) (проект № 202409010253).

Ссылка при цитировании: Би Цзячэнь, Пан Хайхун, Эйдельман Б.Л. Терморегулирование солнечных элементов с помощью наночастиц даун-конверсии // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 237–241. DOI: <https://doi.org/10.18721/JPM.183.248>

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Introduction

The thermal energy in photovoltaic panels originates primarily from solar radiation. When photons in the solar spectrum possess energy exceeding the bandgap energy (E_g), only the portion equivalent to E_g is utilized to drive the photoelectric effect and generate charge carriers, whereas the surplus energy ($h\nu - E_g$) is dissipated as heat within the cell. As illustrated in Fig. 1, silicon-based solar cells ($E_g = 1.12$ eV) exhibit high external quantum efficiency in the 450–1000 nm wavelength range. However, ultraviolet radiation below 400 nm constitutes the dominant source of thermal loss in these devices [2].

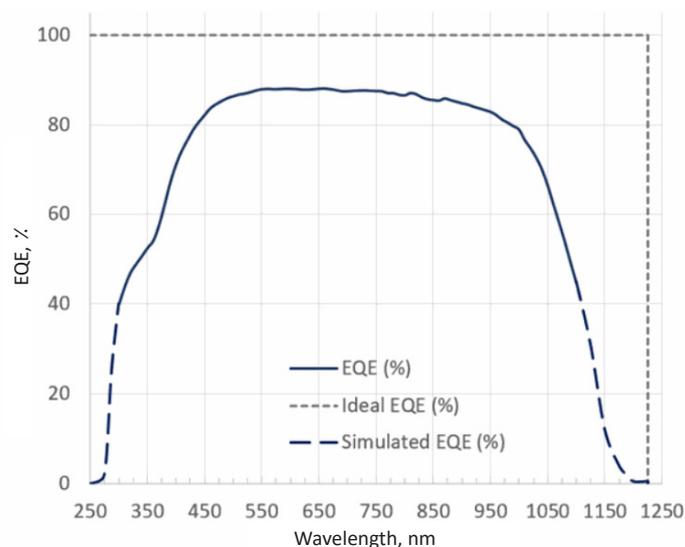


Fig. 1. External quantum efficiency of monocrystalline silicon solar cells

Titanium dioxide (TiO_2) is a familiar n-type semiconductor with a wide bandgap of 3.2 eV in the anatase phase, strong absorption of ultraviolet light, high chemical stability, non-toxicity, and high photocatalytic activity [3, 4]. However, the main limiting factor of pure TiO_2 nanoparticles is its ultrafast recombination rate of charge carriers (measured in nanoseconds). This is because there are a large number of dangling bonds and defects on its surface, which dominates non-radiative recombination, resulting in extremely low photoluminescence quantum efficiency. By selectively doping rare earth ions into the TiO_2 matrix, it can slow down the recombination rate of electron-hole pairs, resulting in unique persistent photoluminescence [5]. Coating rare earth-doped titanium dioxide nanoparticles on the surface of solar cells can effectively convert ultraviolet light into visible light, and its extremely small grains are transparent to visible light, thereby reducing the operating temperature of solar cells and increasing the converted electrical energy [4–5].

Materials and Methods

We first established a thermodynamic model for solar panels coated with Eu^{3+} doped TiO_2 nanoparticles, providing a theoretical basis for the experiments. Fig. 2 shows the transfer of heat and energy from a photovoltaic panel.

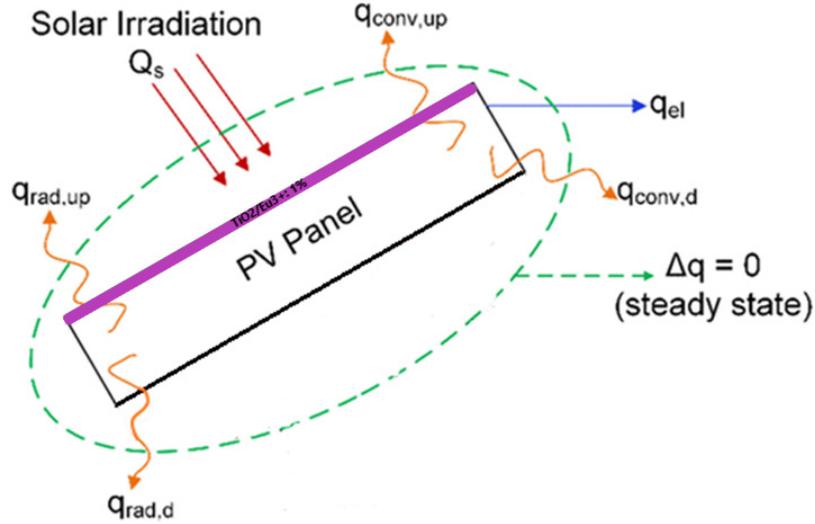


Fig. 2. Schematic diagram of the thermodynamic system of photovoltaic panels

Obviously, the heat balance formula is:

$$P_{heat} = P_{loss}. \quad (1)$$

Total absorbed power of photovoltaic panels (AM1.5):

$$P_{abs} = A Q_S \varepsilon_0, \quad (2)$$

where A is photovoltaic panel area, Q_S is the normal solar radiation, and ε_0 is absorption capacity of the surface of a photovoltaic panel.

Since the band gap of titanium dioxide nanoparticles is 3.0–3.2 eV, they have strong absorption capacity for UVA. The 20 nm grain size is much smaller than the wavelength of visible light (400–700 nm), and the scattering effect is weak, so it is almost transparent to visible light and infrared light. Energy absorbed by 20nm TiO_2 nanoparticles:

$$P_{abs, \text{TiO}_2} = A Q_S \cdot \left[\varepsilon_{\text{TiO}_2, UV} \cdot f_{UV} + \varepsilon_{\text{TiO}_2, vis} \cdot (1 - f_{UV}) \right], \quad (3)$$

where $f_{UV} = 0.05$ (the energy proportion of ultraviolet light in AM1.5), $\varepsilon_{\text{TiO}_2, UV}$ is absorption rate of ultraviolet light by TiO_2 nanoparticles, roughly equal to 0.9, $\varepsilon_{\text{TiO}_2, vis}$ is absorption rate of TiO_2 nanoparticles to visible light is roughly equal to 0.05.

The power absorbed by polysilicon is:

$$P_{abs, Si} = P_{abs} - P_{abs, \text{TiO}_2}. \quad (4)$$

Photoluminescent power:

$$P_{PL} = P_{abs, \text{TiO}_2, UV} \cdot \eta_{PL} = A Q_S \cdot \varepsilon_{\text{TiO}_2, UV} \cdot f_{UV} \cdot \eta_{PL}. \quad (5)$$

Reabsorption and escape power:

$$P_{re-abs} = P_{PL} \cdot EQE(\lambda), \quad (6)$$

$$P_{escape} = P_{PL} \cdot [1 - EQE(\lambda)], \quad (7)$$

where $EQE(\lambda)$ is external quantum efficiency.

Heat accumulation:

$$P_{heat} = P_{abs,Si} \cdot (1 - \eta_{Si}) + P_{abs,TiO_2} \cdot (1 - \eta_{PL}) + P_{re-abs} \cdot (1 - \eta_{Si}). \quad (8)$$

Heat loss:

$$P_{loss} = 2hA(T_S - T_a) + 2\varepsilon\sigma A(T_S^4 - T_a^4), \quad (9)$$

where h is convective heat transfer coefficient, assume $h = 10 \text{ W}/(\text{m}^2 \cdot \text{K})$. T_S is photovoltaic panel temperature, T_a is ambient temperature, $T_a = 23 \text{ }^\circ\text{C}$, ε is surface emissivity, σ is Stefan-Boltzmann constant.

Based on the above formulas, we can derive the theoretical operating temperature of the solar panel coated with Eu-doped TiO_2 nanoparticles at room temperature as $T_S = 319.0\text{K}$.

To better understand the effects of down-conversion photoluminescent nanoparticles on solar panel operating temperatures, we initially developed a thermodynamic model for theoretical analysis. Subsequent experimental validation confirmed the temperature-reduction capability of this approach. For comparative testing, we exposed two $100 \text{ mm} \times 100 \text{ mm}$ polycrystalline silicon solar panels (supplied by Telecom-STV Company) to AM1.5 midday sunlight for one hour: Sample 1 coated with 20 nm $\text{Eu}^{3+}:1\%$ doped TiO_2 nanoparticles, and Sample 2 as an uncoated reference standard. Temperature measurements were recorded throughout the exposure period, followed by electrical performance characterization using a CT-1000 solar module $I-V$ tester.

Results and discussion

The actual measurement results show that the temperature of the solar panel covered with Eu^{3+} doped TiO_2 nanoparticles is 1.8 K lower than the standard one. As shown in Fig. 3, the open circuit voltage V_{OC} and short circuit current I_{SC} have increased slightly, and the photoelectric conversion efficiency has increased by 0.6% (Table 1). The result obtained by theoretical calculation based on the thermodynamic model is 2.5 K . The error of 0.7 K may be because the

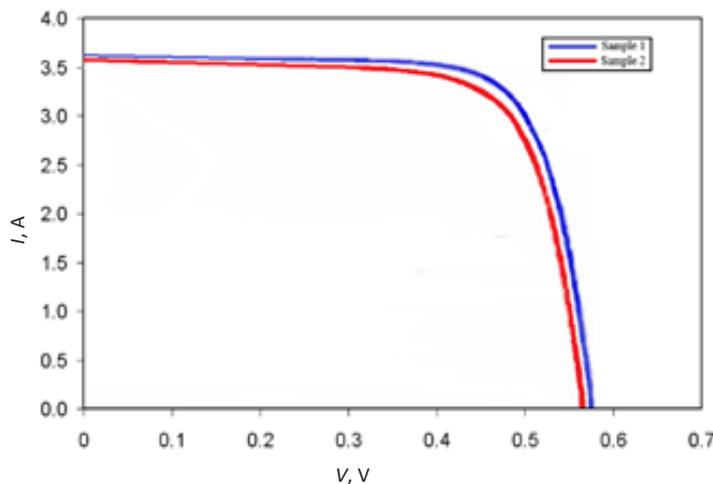


Fig. 3. Current-voltage ($I-V$) curves of two samples



Table 1

Parameters of the studied samples

sample	T , K	V_{oc} , V	I_{sc} , A	η
1	319.7	0.574	3.561	19.5%
2	321.5	0.562	3.553	18.9%

model assumes that the nanoparticles are closely connected and 100% covered on the surface of the solar cell. And all the photons emitted by the titanium dioxide nanoparticles are injected into the silicon matrix. This shows that if the covering technology of the nanoparticles is improved and the anti-reflection layer is added, the temperature of the solar panel can be lower and the efficiency η can be higher.

Conclusion

The effects of down-conversion nanoparticles on both thermal regulation and electrical output of solar cells were systematically investigated. Thermodynamic modeling and controlled experiments demonstrated that this photoluminescent coating strategy reduced the module operating temperature by 1.8 K while simultaneously increasing energy conversion efficiency by 0.6%. However, the theoretical operating temperature remains 0.7 K lower than experimental measurements, indicating that subsequent research requires improvements in the coating process for photoluminescent layers and selection of materials with higher photoluminescence quantum yields.

REFERENCES

1. **Rahmanian S., Rahmanian-Koushkaki H., Omidvar P., Shahsavari A.**, Nanofluid PCM heat sink for building integrated concentrated photovoltaic with thermal energy storage and recovery capability, *Sustainable Energy Technologies and Assessments*. 46 (2021) 101223.
2. sciencetech-inc. <https://www.sciencetech-inc.com/page/quantum-efficiency>. Accessed Mar. 19, 2025.
3. **Mohamed Zikriya, Nadaf Y.F., Vijai Bharathy P., Renuka C.G.**, Luminescent characterization of rare earth Dy^{3+} ion doped TiO_2 prepared by simple chemical co-precipitation method, *Journal of Rare Earths*. 37 (2019) 24–31.
4. **Au V.T., Tran H., Lien N., et al.**, Synthesis of titanium dioxide nanotubes via one-step dynamic hydrothermal process. *Journal of Materials Science*. 49 (2014) 5617–5625.
5. **Henderson M.A.**, A surface science perspective on TiO_2 photocatalysis, *Surface Science Reports*. 66 (2011) 185–297.

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Received 29.09.2025. Approved after reviewing 21.10.2025. Accepted 21.10.2025.