Research Article

Shanfeng Huang*, Xiaoming Shen*, Yuechun Fu, and Huan He

Considering the effect of optical attenuation on photon-enhanced thermionic emission converter of the practical structure

<https://doi.org/10.1515/phys-2021-0041>

received March 06, 2021; accepted May 16, 2021

Abstract: Photon-enhanced thermionic emission (PETE) is a new type of solar cell. The existing papers on PETE research do not consider the structure of actual PETE devices; in practical PETE structure, the original incident light intensity is attenuated by the window layer and the buffer layer (include anode in reflection PETE devices). In this paper, according to two kinds of the common structure of PETE device, the influence of transmission and reflection of sunlight on the conversion efficiency of PETE device is analyzed. Using a light-trapping structure on the cathode of the PETE device is a valid method to reduce the reflection of the incident light. The calculation results show that the optical attenuation has a great influence on the actual photon flux received by the cathode effective layer. Under the condition of reasonable operation of the device, the efficiency of PETE can be improved by reducing the size of the material, improving the light transmittance of the buffer layer and window layer, and using the light-trapping structure.

Keywords: PETE, optical attenuation, cathode structure

1 Introduction

The photovoltaic solar cell is the most widely used, but the reverse current of traditional photovoltaic solar cell rises along with the increasing temperature, resulting in the steep decrease in output efficiency when the temperature reaches a certain range. The working temperature of photovoltaic solar cells is generally less than 400 K [1]. Photo-thermal power generation is also an important way to generate electricity, but the operating temperature of solar power generation is mostly higher than 600 K [2]. If the photovoltaic power generation and photo-thermal power generation can be combined, the total efficiency of the system will be greatly improved. In 2010, a solar energy utilization idea based on semiconductor cathode photon-enhanced thermionic emission (PETE) is proposed by Schwede et al. from Stanford University [3]. PETE combines photon excitation and heat excitation, and it uses both photon and solar radiation heat energy [4,5]. When the temperature of cathode is low, the process of photoelectric conversion is that the high-energy photons excite the electrons of valence band to the vacuum. It is called photoexcited. When the cathode temperature is high (more than 1,000 K), the PETE converter mechanism is the same as the thermionic electron emission (TEC) appropriately, and the efficiency of PETE and TEC is almost the same [6]. The resulting current is partly photoexcited, partly PETE, and the rest is TEC. The noticeable advantage of PETE is making use of solar cell radiation as much as possible, as the system efficiency goes up with the increase in temperature [7]. Theoretically, the total efficiency exceeds 50%. Most of the existing literature about PETE regards the cathode structure as a single rectangular bulk. Therefore, the PETE efficiency calculated is relatively high.

PETE is different from traditional photovoltaic solar cells; the significant components of a PETE generator are the cathode and the anode which are set at appropriate intervals. A p-type semiconductor is chosen for the

* **Corresponding author: Shanfeng Huang**, Center of Ecological Collaborative Innovation for Aluminum Industry in Guangxi, Guangxi Key Laboratory of Processing for Non-ferrous Metal and Featured Materials, School of Resources, Environment and Materials, Guangxi University, Nanning 530004, China, e-mail: 474050520@qq.com

* **Corresponding author: Xiaoming Shen**, Center of Ecological Collaborative Innovation for Aluminum Industry in Guangxi, Guangxi Key Laboratory of Processing for Non-ferrous Metal and Featured Materials, School of Resources, Environment and Materials, Guangxi University, Nanning 530004, China, e-mail: docsjh@gxu.edu.cn

Yuechun Fu, Huan He: Center of Ecological Collaborative Innovation for Aluminum Industry in Guangxi, Guangxi Key Laboratory of Processing for Non-ferrous Metal and Featured Materials, School of Resources, Environment and Materials, Guangxi University, Nanning 530004, China

cathode, the n-type semiconductor is chosen for the anode, and the work function of cathode and anode has to satisfy the following relation: When photon flux irradiates the surface of cathode in steady state, high-energy photons ($h\nu \geq E_g$) excite electrons of top valance band and jumping into the conduction band. These electrons are non-equilibrium carriers with high energy. Low energy photons are absorbed by the cathode in the form of infrared thermal energy, which is used in two parts: heating the non-equilibrium carriers in the conduction band so that they have enough energy to escape from the cathode, the others is for thermionic emission effect [6]. We assume that electrons reaching the vacuum level do not consume energy during flying across the gap between electrodes. Once an anode receives electrons from the cathode, there is a potential difference produced between the cathode and anode. If the cathode and anode are switched with a stored device, the device can be used to generate electricity [3,8].

The ideal situation is the cathode can be regarded as bulk with only a cathode efficient layer. A common transmission cathode of PETE has a window layer such as glass, gemstone, or high transmission material. Behind the window layer is a buffer layer and then the effective layer of the cathode. The buffer layer can reduce the photoelectron recombination rate, can protect the effective layer of the cathode, and is a compensation material for lattice mismatch. Different cathode structures and production processes that increase the types and layers of cathode materials, the reflection, and transmission of light paths are more complex. The anode of reflection PETE model must use a high transmittance material to ensure the number of photons the cathode receives; however, the anode also reflects part of the incident light and then reduces the number of photons received by the cathode, thus affecting the current density of PETE. In the same way, the impact of structures and productive ways of the cathode in the reflection PETE model must be considered. This paper will give two examples to discuss the influence of transmission loss and reflection effect on PETE efficiency when photons entering into the cathode.

2 Analysis

2.1 The absorption coefficient of the device

The ideal light intensity can be expressed by a function that is relevant to the thickness of cathode and absorption

coefficient of material (cathode of reflection PETE model can be regarded as semi-infinite bulk) $I_0 = I \cdot \exp(-ax)$, where a is a wavelength-dependent absorption coefficient, and x is the distance the light travels in the material perpendicular to the front surface. The energy of light is the result of the number of photons and the energy of a single photon. The more common photon flux is used to calculate PETE efficiency. For the light of the same frequency, the intensity of light depends on the number of photons per unit area per unit time:

$$G_0 = G \cdot \exp(-ax). \quad (2.1.1)$$

Ideally, because of the reflection effect of the anode, the cathode cannot receive all incident photons, and part of photons is reflected by anode and cathode. The cathode of transmission-mode PETE has window layer and buffer layer, and they can be transmitted by photons; the photons are reflected by cathode as well (including anode in reflection PETE model), and the reflected light and transmitted light enter into other interfaces of cathode and anode and the process is repeated. In the process, photons are absorption by the window layer, buffer layer cathode, and anode. The sum of multiple reflection and transmission of light eventually toward the cathode can be treated as effective incident light intensity. By the law of the propagation of light in a medium:

$$\sigma + \rho + \tau = 1, \quad (2.1.2)$$

where σ is the absorption, ρ the reflectivity, and τ the transmissivity.

In transmission-mode cathode, we only need to calculate the photon current density after experiencing various reflection and transmission losses to reach the cathode effective layer and multiply by the absorption rate, cause of the strong absorption of photons in the cathode effective layer GaAs, the absorption rate of one reflection is:

$$1 - R - (1 - R)^2 \exp(-aL). \quad (2.1.3)$$

In the reflective cathode, because the cathode is regarded as a semi-infinite bulk, the incident light cannot reach the other side of the cathode, and thus the transmissivity is 0 and the absorption rate is $1 - R$ [1,2,9].

2.2 Photon yield on the cathode surface

For transmission-mode cathode, a common internal structure is shown in Figure 1. From top to bottom are the window layer, the buffer layer, and the cathode effective layer.

The original incident light first reaches the surface of the cathode effective layer through three paths: ① The

light traverses through the window layer buffer to the effective layer. ② The light traverses through the window layer and reaches the buffer layer and is reflected by the buffer layer and then reaches the front surface of the window layer, and then is reflected again by the front surface of the window layer and reaches the effective layer in the route of ①. ③ The light enters the window layer and is reflected twice by the front surface and the back surface, respectively, and reaches the effective layer surface. The combined photon flux of ①–③ is [10–12]:

$$G_1 = M[1 + R_0 R_1 \exp(-2\alpha_0 d_0) + R_0^2 R_1^2 \exp(-4\alpha_0 d_0)], \quad (2.2.1)$$

where $M_{\text{trans}} = G_{\text{sun}}(1 - R_0)(1 - R_1)\exp(-\alpha_0 d_0)\exp(-\alpha_1 d_1)$.

Next, the light G_1 is reflected by the effective layer, and the propagation direction of the light path is opposite to the original incident light, which can be divided into three steps: ④ The reflected light is reflected by the front surface of the buffer layer and reaches the effective layer; ⑤ and ⑥ repeat the steps ② and ③ and reach the effective layer. After that, the ④–⑥ processes will cycle. The total photon flux that finally reaches the effective layer surface can be calculated with a geometrical sequence:

$$G_{\text{sun-trans}} = \frac{G_1}{1 - q_0} R_2 [1 - R_2 + (1 - R_2)^2 \exp(-2\alpha_2 W)], \quad (2.2.2)$$

the common ratio of which is:

$$q_0 (q_0 < 1) = [R_1 \exp(-\alpha_1 d_1) + R_0(1 - R_1)^2 \exp(-2\alpha_0 d_0) \exp(-2\alpha_1 d_1) + R_0^2 R_1(1 - R_1)^2 \exp(-4\alpha_0 d_0) \exp(-2\alpha_1 d_1)].$$

R_i is the reflectivity of material in the transmission model.

Figure 1: Cathode model of transmission PETE device.

In the reflection PETE model, in the transmission PETE device, sunlight traverses through the anode and reaches the cathode to excite the emission of the cathode electron image anode. N-type material as anode material must have high light transmittance so that as many photons as possible can be irradiated on the cathode surface, the anode and cathode are separated by a vacuum, and the light traverses through the anode and reaches the cathode to produce a photoconductive effect, thus generating a potential difference between the anode and cathode. Figure 2 shows the examples of structure of anode – vacuum – buffer layer – cathode effective layer.

The analysis is similar to the transmission cathode. The reflectivity of the front and back surfaces of the anode is equal. The formula of photon flux density finally reaches the surface of cathode effective layer:

$$G_{\text{sun-ref}} = \frac{G_2}{1 - q_1} (1 - A_2), \quad (2.2.3)$$

$$G_2 = M_{\text{ref}}(1 - A_1)[1 + A_0 A_1 + A_0 A_1 (1 - A_0)^2 \times \exp(-2\alpha_3 d_3) \exp(-\alpha_4 d_4) + A_0^3 A_1 (1 - A_0) \exp(-4\alpha_3 d_3)], \quad (2.2.4)$$

where the common ratio of geometric progression is:

$$q_1 = \exp(-2\alpha_4 d_4) A_0 (1 - A_1) \times [1 - A_1 + (1 - A_0)^2 \exp(-2\alpha_3 d_3) + (1 - A_0)^2 \exp(-4\alpha_4 d_4)].$$

A_i is the reflectivity of material in the reflection model.

2.3 Light trapping structure of the cathode

The light-trapping structure on the cathode surface can be realized by chemical etching. On the micro-level, the light trapping structure is a certain depth of small

Figure 2: Cathode structure model of reflection PETE device.

pits arranged periodically on the cathode surface. In a small cavity, except for the entrance of light, the light intensity of a certain element position can be written as: $I(r) = E(r)E(r)^*$, where $E(r)$ is the electric field strength of a point in the cavity. Think of the pit as a cavity; the total light intensity in the cavity is $I_{\text{sum}} = \iint_S I(r) dS$, and the light intensity escaping from the cavity is $I_e = \iint_{S_0} I(r) dS$, where S_0 is the size of the cavity opening area and S is the internal surface area of the cavity. Light is reflected many times in the cavity, and the light intensity reaching a point is inversely proportional to the square of the distance from the point to the reflection point; the escape probability can be approximated by the formula [13,14]:

$$P = \frac{S_0}{S + S_0}. \quad (2.3.1)$$

In a planar cathode with light-trapping structure, the photon flux entering the cathode is divided into two parts: a part flux is from the light trapping structure, the other is from the smooth plane. The probability of photon escape is used as the reflectivity of the cathode. The reflectivity of the plane part of the cathode uses the optical reflectance of the planar material. If there are M pits on the surface of a material with area S_s , thickness L , and reflective of smooth surface R , the reflectivity of the smooth plane is the inherent reflectivity of the material, and the reflectivity of the small pit with light-trapping structure is the probability that photons escape from the small pit. The photon flux can be absorbed by the cathode efficiency layer with light-trapping structure:

$$G_{\text{yield}} = G_{\text{sun}} \left[\frac{MS_0}{S_s} \left(1 - \frac{S_0}{S + S_0} - (1-R)^2 \exp(-\alpha W) \right) + \frac{S_s - MS_0}{S_s} (1 - R - (1-R)^2 \exp(-\alpha W)) \right]. \quad (2.3.2)$$

For different pit shapes, the probability of photon escaping from the cathode material surface is different. The number of pits on the cathode surface also determines the reflectivity of the cathode. Moreover, the internal surface area of the small pit can be increased by making pits of smaller size on the inner surface, which can be deduced from the escape formula, and the denominator value can be increased by increasing the internal surface area of the small pit. Figure 3 establishes three kinds of pit models: hemispherical pits, cone

pits, and elliptical pits. The photon yield on the three cathode surfaces with light-trapping structure can be calculated by equation (2.3.2).

2.4 PETE model in the detailed balance limit

A more approximate PETE process can be obtained in a detailed balance limit model. The detailed balance limit model of PETE has been summarized by Schwede et al. thoroughly [3]. The following model satisfies the condition: Each electron can jump from valence band to conduction band by a photon ($h\nu \geq E_g$), the effect of anode reverse current on cathode conduction band electrons is ignored, the recombination only considers the radiation recombination effect, the effects of low-temperature plasma phenomena are not considered, the energy band of both anode and cathode is flat band condition, and there is no bias voltage and potential barrier on the cathode surface [4,6,15–18].

Based on the conservation of the number of particles, the number of photons received at the cathode of PETE is equal to the number of electrons PETE has converted to photoelectricity and the number of photons recomposed in the cathode: $G_{\text{sun-cathode}} = G_{\text{PETE}} + G_{\text{recombination}}$.

For different models of PETE:

$$G_{\text{sun-cathode}} = \begin{cases} G_{\text{sun-trans}}(\text{transmission PETE model}) \\ G_{\text{sun-ref}}(\text{reflection PETE model}). \end{cases}$$

In the PETE process, the internal recombination of the cathode can be considered as only radiation recombination:

$$G_{\text{recombination}} = B(np - n_0p_0)/W, \quad (2.4.1)$$

where W is the thickness of efficient cathode; the recombination coefficient can be calculated by the equation:

Figure 3: The light-trapping structures shown are semicircular pits, cone pits, and elliptical pits (The light-trapping structure in this figure is exaggerated. The actual light-trapping structure can be micron level or nano-level according to the requirements and technology).

$$B = \frac{1}{W} \frac{1}{n_0 p_0} \frac{2\pi}{h^3 c^2} \int_{E_g}^{\infty} \frac{E^2 dE}{\exp(E/kT_c) - 1}, \quad (2.4.2)$$

where n_0 is the equilibrium electrons concentration and p_0 the equilibrium holes concentration. The current generated by the cathode is divided into the current generated by photons and the current generated without illumination, which is thermionic emission:

$$G_{\text{PETE}} = (J_c - J_a)/qW, \quad (2.4.3)$$

where J_c is the PETE current and J_a the thermionic electron current density without incident photons.

$$J_a = A^* T^2 \exp(\phi_c/kT_c), \quad (2.4.4)$$

where A^* is the Richardson constant and ϕ_c the work function of efficient cathode.

The non-equilibrium carrier concentration can be expressed as:

$$\Delta n = \sqrt{\left(p_0 + n_0 + \frac{J_a}{qn_0 BW}\right)^2 + \frac{4G}{BW}} - \left(p_0 + n_0 + \frac{J_a}{qn_0 BW}\right). \quad (2.4.5)$$

The cathode emission current is:

$$J_c = A^* T_c^2 \exp(\phi_c/kT_c) \frac{n_0 + \Delta n}{n_0}. \quad (2.4.6)$$

The system conversion efficiency of PETE is:

$$\eta = \frac{J_c/q}{G_{\text{sun}}}. \quad (2.4.7)$$

3 Results and discussion

The spectrum of sunlight received by the earth is AM1.5 when the cathode material is GaAs, and the light that can be absorbed satisfy the conditions: $\lambda \leq 860$ nm. The concentration of incident solar radiation is 500. The band gap of GaAs is 1.42 eV, corresponding maximum absorption wavelength is about 860 nm, which means the wavelength less than 860 nm can be absorbed by GaAs. Integrate the area of AM1.5, we can know the photon flux density which wavelength less than 860 nm is $(9.5E + 19 \text{ cm}^2/\text{s})$. The temperature range (300–1,000 K) is satisfied in the following discussion: the highest temperature is below the melting point of GaAs (~1,513 K), and the lowest temperature is room temperature. We assumed that the direction of sunlight incidence is

perpendicular to the cathode surface and ignored the role of photons and other microscopic particles such as electrons in reflection PETE. We choose glass and AlGaAs as the window layer and buffer layer in both model, cause the lattice constant of the buffer layer needs to be close to the effective layer, and the bandgap of the buffer layer is higher than the effective layer to make the photon in the propagation process as little as possible to produce the external photoelectric effect.

In the transmission-mode PETE model, we choose glass as the window layer and AlGaAs as the buffer layer for calculation. α_3 and α_4 are the absorption coefficients of the windows layer and buffer layer, and d_3 and d_4 the thickness of the window layer and buffer layer, respectively. We choose glass as the window layer material in which reflectivity can be calculated: $R_0 = (r_g - 1)^2 / (r_g + 1)^2$, AlGaAs as the buffer layer: $R_1 = [(r_g - r_A)^2 + \kappa_A^2] / [(r_g + r_A)^2 + \kappa_A^2]$, p-type GaAs as the efficient layer of a cathode the doping concentration of which is: $5 \times 10^{18} / \text{cm}^3$, and the reflectivity of GaAs is: $R_2 = [(r_A - 1)^2 + \kappa_A^2] / [(r_A + 1)^2 + \kappa_A^2]$. r_g , r_A , and r_G represent the refraction of glass, AlGaAs, and GaAs, respectively. κ_A and κ_G are the extinction coefficients of AlGaAs and GaAs, respectively. α_0 , α_1 , and α_2 are the absorption coefficients of the window layer, buffer layer, and efficient layer. d_0 , d_1 , and d_2 are the thickness of the window layer, buffer layer, and efficient layer.

In reflection PETE, the material of anode we choose is the n-type doped diamond. We define the cathode thickness as 0.01 cm; as the photoelectron cannot reach the other side of the cathode, we increase the thickness value of the cathode appropriately in the reflection PETE. The reflectivity of the n-type diamond, buffer layer, GaAs (>500 K) for red light is 0.15, 0.3, 0.3, respectively [18] (Figure 4).

The emission current of the cathode is also affected obviously. From the formula point of view, the reason for this difference is that the decrease in non-equilibrium carriers leads to the decrease in the numerator value of equation (2.4.3). In a physical sense, the decrease in the number of photons on the cathode surface leads to the decrease in the number of photoexcitation electrons in the conduction band within the PETE process. The number of electrons escaping from the cathode using low-energy photons ($h\nu < E_g$) to overcome the electron affinity is greatly reduced. The precise number of photons received by the cathode needs to consider the reflection and transmission loss of the path traveling in the PETE structure of the cathode and anode. Figure 5 indicates that the PETE quantum efficiency obtained using the

Figure 4: The comparison of the number of non-equilibrium carriers without considering the attenuation during the light propagation PETE, the transmission PETE cathode, and the reflection PETE cathode.

ideal number of photons received by the cathode is quite different from that obtained by considering the number of photons received by the material with multiple material interfaces. The same principle can be used to explain the loss of photons in the reflection PETE model.

For comparing the effect of the light-trapping structure on the absorptivity, we assign a term to the percentage form which represents the proportion of light-trapping structure on the cathode surface. The radius of the opening circle of the trap structure is 2×10^{-4} cm. Figure 6 shows that the light-trapping structure with a cone depth of $2/3$ of the opening radius has a lower reflectivity than that of a semicircular one with the same circular opening area. At the same depth, the ellipsoidal light-trapping structure has a lower reflectivity than the conical one. With the increase in the proportion of light trapping structure, the photon yield on the surface is also increasing.

Assuming that special engraving technology is used in the inner surface area of the light trapping structure, the light-trapping structure has a substructure, and the internal surface area can be further increased, then

Figure 5: The quantum efficiency of ideal cathode, transmission PETE cathode, and reflection PETE cathode.

Figure 6: The relationship between the ratio of different light-trapping structures and photon yield.

the incident light will be more difficult to escape from the light trap structure. We define an internal surface area increasing coefficient n . The photon yield increases with the increasing coefficient: $P = S_0 / (nS + S_0)$. Figure 7 demonstrates that when the surface area of the substructure increases slightly, the increase in photon yield will be very significant. However, with the continuous increase in the substructure coefficient, the increase in photon yield is very weak.

Figure 8 shows that in a certain range (<0.005), the change in window layer thickness has a greater impact on the photon yield on the cathode surface than on the buffer layer, and a small change in the window layer thickness will strongly affect the photon yield on the cathode surface. Reducing the thickness of the window layer and buffer layer as much as possible is

Figure 7: The relationship between the increased coefficient of internal surface area and the yield of the cathode surface.

Figure 8: Relationship between the thickness of the window layer in the transmission cathode and the number of photons received by the effective layer of the cathode.

an effective way to increase the photon yield on the cathode surface under the condition of meeting other characteristics requirements. Figure 9 manifests that the efficiency of PETE with ellipsoidal light trapping structure is remarkably higher than that with the planar cathode. With the increase of the increasing coefficient, the conversion efficiency of PETE at various temperatures also increases. It shows that the use of the light-trapping structure and the increasing coefficient of the light-trapping structure have a positive effect on the conversion efficiency of the PETE device.

4 Conclusion

In this paper, we present two common structures of cathode and anode in the PETE converter, considering the loss of light traversing through material and loss of photons that are reflected but not received by the cathode. Many processes and details have been idealized in this paper, but the theory of photon flux density decreasing on the cathode effective layer surface because of the optical path needs to be considered. At the same time, we use the model of light entering trap to quantify the effect of light trapping on the photon yield of the material surface. For PETE devices with different interelectrode structures, the method proposed in this paper can provide a reference for calculating PETE efficiency in detail limit balance conditions. The methods of increasing the actual number of receiving photons on the cathode can add a coating to the material interface that reduces reflectivity, such as a subtractive film, or control

Figure 9: Conversion efficiency of transmission PETE device with the planar cathode and ellipsoidal structure with different amplification coefficient.

the size of the material of cathode and anode thickness under other conditions, such as heat dissipation and size. The light-trapping structure is a kind of structure that can effectively improve the photon yield of PETE devices. When the efficiency of the PETE converter is calculated accurately, the loss of photon propagation in the PETE device is not negligible.

Conflict of interest: Authors state no conflict of interest.

References

- [1] Bambawale MJ, Sovacool BK. China's energy security: the perspective of energy users. *Appl Energy*. 2011;88(5):1949–56.
- [2] Fang X, Li D. Solar photovoltaic and thermal technology and applications in China review article. *Renew Sustain Energy Rev*. 2013;23:330–40.
- [3] Schwede JW, Bargatin I, Riley DC, Hardin BE, Rosenthal SJ, Sun Y, et al. Photon-enhanced thermionic emission for solar concentrator systems. *Nat Mater*. 2010;9:762–7.
- [4] Acikkalp E, Kandemir SY. Performance assessment of the photon enhanced thermionic emitter and heat engine system. *J Therm Anal Calorim*. 2020.
- [5] Shourong X, Qingcheng Z, Yonghong G, Liming X. Experimental investigation on the properties of reflecting power on GaAs surface changing with the temperature. *J Trans Technol*. 1996;6.
- [6] Weidong T. Based on the mechanism of photon-enhanced electron emission for solar energy converters. Xi'an, China: Xi'an Institute of Optics & Precision Mechanics, Chinese Academy of Sciences; 2014.
- [7] Chen YC, Deng SZ, Xu NS, Chen J. Energy-tunable photon-enhanced thermal tunneling electrons for intrinsic adaptive full spectrum solar energy conversion. *Appl Phys Lett*. 2020;116:063002.
- [8] Diao Y, Liu L, Xia SH. Photon-enhanced thermionic emission solar energy converters with GaAs wire array cathode under external electric field. *Appl Nanosci*. 2020;10:807–17.

- [9] Enke L, Bingsheng Z, Jinsheng L. The physics of semiconductors. Publ House Electron Ind. 2017;7:85–258.
- [10] Kun H. Semiconductor physics. Beijing, China: Science Press; 1958.
- [11] Ghatak A. Optics. Beijing, China: Tsinghua University Press; 2019.
- [12] Liu YZ, Moll JL, Spicer WE. Quantum yield of GaAs semitransparent photocathode. Appl Phys Lett. 1970;17(2):60–2.
- [13] Yong Q, Shimeng F. Effect of multi-crystalline silicon pit-trap shape on the optical reflectance. Acta Optical Sin. 2012;3:32–2.
- [14] Kunxia W, Shimeng F, Huatian X, Jiadong T, Shuquan Y. Relation between the multicrystalline silicon surface structure and the pit-trap effect. Acta Optical Sin. 2012;3:32–3.
- [15] Varpula A, Prunnila M. Diffusion-emission theory of photon enhanced thermionic emission solar energy harvesters. J Apply Phys. 2012;112:044506.
- [16] Segev G, Rosenwaks Y, Kribus A. Efficiency of photon enhanced thermionic emission solar converters. Sol Energy Mater Sol Cell. 2012;107(1):125–30.
- [17] Haoming C. Analysis of emission characteristics in photon enhanced thermionic conversion. Zhejiang, China: Zhejiang University; 2019.
- [18] Yang Y, Cao WW, Xu P, Zhu BL, Bai YL, Wang B, et al. Temperature-dependent analysis of solid-state photon-enhanced thermionic emission solar energy converter. Energies. 2020;13:1554.