

Research Progress on Improving Photovoltaic Conversion Efficiency in Lunar Rovers

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Abstract. With the deepening of human exploration of the moon, the requirements for essential technology applications such as the energy reserve of the lunar rover have also increased. Moreover, a steady supply of energy is what the moon rover needs, and how to obtain a reliable energy supply is also a concern of humans. Improving solar energy conversion efficiency is a feasible way to solve this problem. The paper reviews the measures and research progress of improving the solar energy conversion efficiency of the lunar vehicle. Firstly, analyze the selection of solar photovoltaic panel materials, and introduce the research and selection of various materials. Secondly, summarize the methods to reduce the amount of lunar dust in contact with solar panels. Lastly, analyze the design of solar panel structure, the insolation efficiency under different systems, the control principle, and its characteristics.

Keywords: Lunar Rover, Photovoltaic Conversion Efficiency, solar panel materials, solar panel structure.

1. Introduction

In recent years, with the deepening of human exploration of the moon, the requirements for essential technology applications such as the energy reserve of the lunar rover have also increased. Moreover, a steady supply of energy is what the moon rover needs, and how to obtain a reliable energy supply is also a concern of humans. Improving solar energy conversion efficiency is a feasible way to solve this problem. This paper reviews various measures to improve the efficiency of solar photovoltaic conversion on lunar rovers and their research progress. It mainly reflects in the choice of materials, a decrease in lunar dust, solar panel structure, and other aspects. It also analyzes their strengths and weaknesses and provides references and suggestions to improve the solar energy conversion efficiency and related applications in the lunar rover in the future.

A lunar rover is a dedicated vehicle that can drive on the surface of the moon and complete complex tasks such as lunar exploration, investigation, collection, and analysis of samples. It consists of unpiloted and piloted rovers. Currently, most are unpiloted lunar rovers, which consist of a wheeled chassis and an instrument bay powered by a combination of solar cells and batteries. The rover's chassis is made of an aluminium alloy tubular material, hinged in the middle to store things. Each aluminium wheel has its electric drive and mechanical brakes. The tire is made of a wire mesh of woven steel coated with zinc. The technical key to the rover's design is the mechanical structure and energy and heat issues.

A day on the moon lasts a little more than 27 days on Earth. So, the gap between day and night on the moon is as large as 14 days on Earth. That means the rover can work up to 14 days after landing on the moon. After entering the moon night, because the rover does not have access to light to generate electricity, it goes into hibernation. Therefore, to ensure the lunar rover's everyday activities on the moon, it needs to obtain sufficient energy during its 14 days of work quickly. In addition, the moon's

surface is uneven, and the rover will need to overcome much resistance to move, requiring a constant supply of energy. Since the fuel supply in outer space is not convenient, solar energy is a kind of ideal energy because of its clean, safe, abundant resources, wide distribution, and reliable technology. The extreme environment of the moon also requires the rover energy system to have strong environmental adaptability to meet the needs of long-term power generation and storage. As a national essential research and development project of science and technology, the task of the lunar rover is complex, challenging and demanding. It is urgent to explore the overall scheme of the energy system, analyze the future development direction of energy technology, sort out the standard key technologies, reduce the number of critical problems and shorten the research cycle.

This paper combines the current research status for three specific problems (The choice of materials, and the reduction of lunar dust, the improvement of solar panel structure), analysing different ways to improve energy conversion efficiency, narrating their advantages and disadvantages, and in the actual application combining with the real situation for the more appropriate method selection suggestions. Through discussing three questions of the selection of photovoltaic materials, the reduction of monthly dust and the improvement of the structure of solar panels with the level of scientific and technological development today, some suggestions to improve the energy conversion efficiency of the lunar rover are proposed. In addition, the prospects of improving the energy conversion efficiency of the lunar rover are presented.

2. Material selection of solar photovoltaic panels for the lunar rover

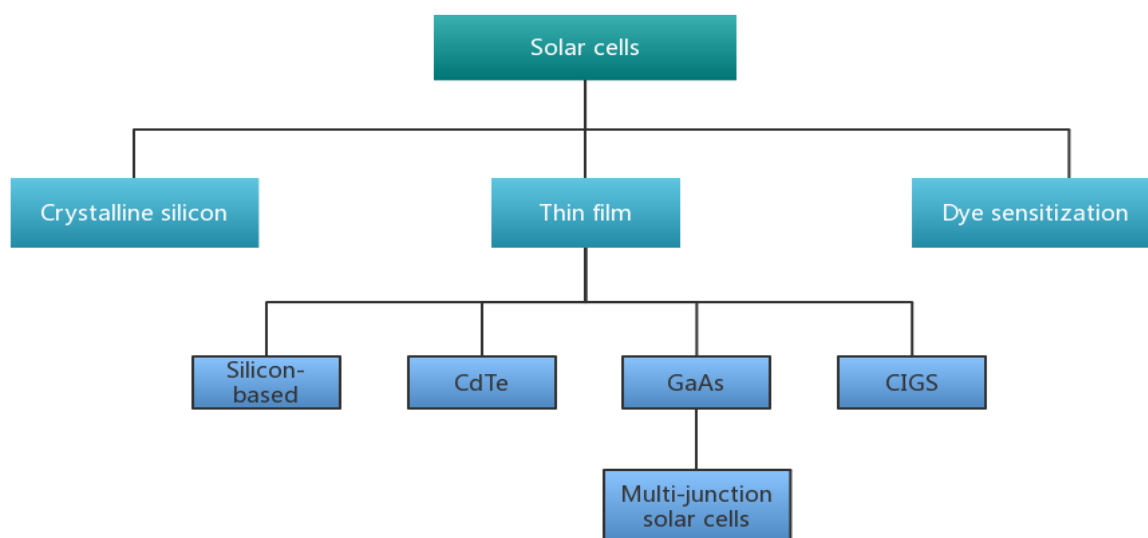


Figure 1. Schematic diagram of solar cell classification

The energy supply of the lunar rover is a fundamental problem in lunar exploration. Furthermore, on the moon, there is plenty of light during the day and less dust in the atmosphere. In addition, suitable solar photovoltaic materials can indirectly improve solar energy conversion efficiency, improve energy reserve, and broaden the scope of lunar exploration [1]. Therefore, selecting suitable solar photovoltaic panel materials is the key to solving the energy supply problem of the lunar rover. This paper illustrates the basic principle of solar cells and analyses the advantages and disadvantages of various thin film solar cells. Finally, the most suitable materials for the moon are selected to explore their main benefits and improvement methods deeply. Figure 1 shows the schematic diagram of solar cell classification.

2.1. Thin-film solar cells

Due to excellent flexibility, thin-film solar cells can be made into non-planar structures, which expands their application scope [2]. Based on these reasons, this part mainly focuses on using thin-film solar cells in the lunar rover. Thin film solar cells are mainly composed of a glass substrate layer,

transparent conductive film layer, semiconductor layer (PN junction), and metal electrode layer [3]. A typical solar cell is essentially a semiconductor diode (P-N junction) bar that converts solar radiation into electricity depending on the photovoltaic effect. Photovoltaic power generation can directly convert luminous energy into electricity by using the photovoltaic effect of the semiconductor interface [4]. Figure 2 shows the Photovoltaic effect principle.

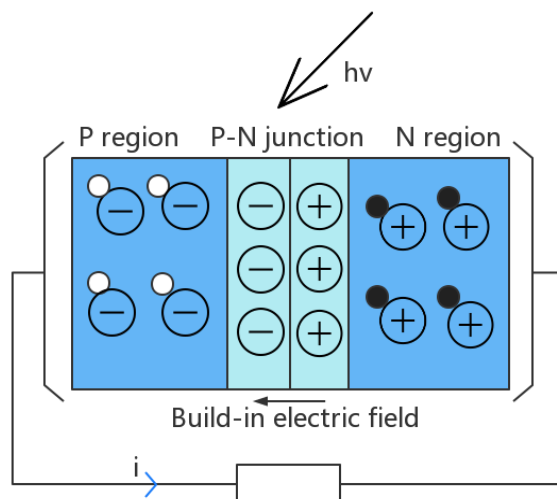


Figure 2. Photovoltaic effect principle

2.2. The types of thin film solar cell materials

The solar cell is the most crucial component of photovoltaic power generation technology [5]. There are four kinds of thin-film solar cells which can be used in China commercially: Silicon-based thin-film solar cell; Cadmium telluride (CdTe) thin-film solar cell; Gallium arsenide (GaAs); thin-film solar cell; Copper indium gallium selenium (CIGS) thin-film solar cell [4]. Table 1 compares the characteristics of several thin-film solar cells [6].

2.2.1. Silicon-based thin-film solar cells

Since solar cells appeared, crystalline silicon cells have played the most crucial role in the photovoltaic cell market. However, in the industrialized development process of commercializing the traditional silicon solar cells, a disadvantage of the conventional crystalline silicon solar cells is amplified gradually. The light absorption layer of conventional crystalline silicon solar cells is thick. For this reason, they consume plenty of limited silicon resources, and their production cost cannot be further reduced. Nevertheless, silicon-based thin-film solar cells only need a light absorption layer a few μm thick to achieve the same or even higher photoelectric conversion efficiency than traditional crystalline silicon [7].

Although the conversion efficiency of silicon-based thin-film solar cells is low, their manufacturing cost is low. Therefore, the industrialization degree is the highest at present [8]. The mainstream silicon-based thin-film solar cells are mainly divided into three types: polycrystalline silicon thin-film solar cell, amorphous silicon thin-film solar cell and microcrystalline silicon thin-film solar cell: (1) Crystalline silicon thin-film solar cell, not only has the advantages of high conversion efficiency, low material toxicity and wide range of raw materials of traditional bulk crystalline silicon photovoltaic materials, but also has the advantages of saving crystalline silicon resources and reducing manufacturing costs of new thin-film photovoltaic materials [7]. (2) Amorphous silicon is a direct band gap semiconductor with a broad light absorption range. Therefore, amorphous silicon thin-film solar cells can be made very thin. Furthermore, the total thickness of light absorption film is about $1\mu\text{m}$. However, due to the insufficient light band gap of amorphous silicon, their efficiency in the infrared region of solar energy is very low. It becomes a significant factor which can limit their development. If these problems can be solved, the cheap production and simple procedure of amorphous silicon will play a more critical role in promoting the industrialization

of solar energy [9]. (3) With the gradual deepening of the research, it has been found that the crystal size of polycrystalline silicon film cannot show good photoelectric conversion performance until it reaches more than 100 μ m [7]. In addition, the preparation technology compatible with amorphous silicon can be adopted for microcrystalline silicon. It can not only save materials but also facilitate low-temperature deposition in large areas so that it can be deposited on many cheap substrate materials and improve stability and efficiency [9].

Table 1. Comparison of characteristics of several thin-film solar cells [6]

Comparison factors	Silicon-based thin-film solar cells	CIGS	CdTe	GaAs
Main material	Silicon	Compounds of copper, indium, gallium and selenium	Compounds of tellurium and cadmium	Compounds of gallium and arsenide
Conversion efficiency	Laboratory :20.5%; components :6-10%	Laboratory :21.7%; components :10%-14%	Laboratory :21.0%; components :8%-13%	Laboratory :28.4%; components: 9%-12%
The cost of materials	The price of high-quality transparent conductive film (TCO) glass is high.	The cost of the target is higher than that of the substrate.	The cost of materials is 30%-50% less than that of silicon-based thin-film solar cells.	Gallium arsenide single crystal is difficult to form and expensive.
Advantages	Low cost; flexible substrate available; mature development; mass production	Stable raw material; the highest efficiency; flexible village bottom available	High efficiency; flexible substrate available; mature development; mass production	High efficiency; cheap Ge substrate available
Disadvantages	Low conversion rate and poor stability	The process is not standardized; the reservation of aluminium and nickel is limited	The film cost is the highest. cadmium is highly toxic; the deposit of natural tellurium is limited	Lattice matching is difficult; crystal defects and misalignments are easy to occur

2.2.2. CIGS thin-film solar cells

CIGS is an abbreviation for thin-film solar cell $\text{CuIn}_x\text{Ga}(1-x)\text{Se}_2$, a crystal thin-film solar cell with the best ratio of copper, indium, gallium, and selenium. CIGS is the critical technology for composing panels [2]. CIGS, which has a more than 20% photoelectric conversion rate, are comparable to the popular monocrystalline silicon solar cells. Furthermore, its strong ability to resist radiation makes it have a photoinduced attenuation effect in the surface area of the power generation and application of small satellite. Moreover, it is very suitable for photovoltaic building integration [10]. In general, CIGS mainly has the following advantages: (1) Strong light absorption capacity. (2) Excellent power generation stability and high conversion efficiency. (3) Long daytime power generation time, high power generation, low production cost and short energy recovery cycle [2]. However, its disadvantages are also prominent. Firstly, it has a toxic element in its buffer (CdS). In addition, its production process is also very complex so the corresponding investment will be higher. Many companies cannot afford the high production cost [10].

In addition, CIGS can be fabricated on flexible substrates, significantly broadening the application field [11]. As shown in Figure 3, the structure of the flexible CIGS is not much different from that of the conventional CIGS with a glass substrate. A typical flexible CIGS cell structure includes a flexible substrate (usually metal or plastic), a back electrode (Mo), an absorbing layer (CIGS, a P-type semiconductor thin film material with chalcolite structure), an N-type buffer layer (CdS) and a transparent conductive window layer (I-ZnO and ZnO: Al thin films). The last is the Ni/Al/Ni gate electrode. An anti-reflection film MgF_2 is usually plated on the top to increase the number of photons entering the cell [11].

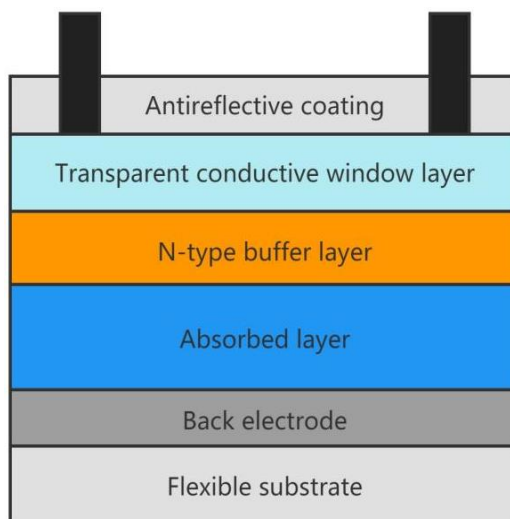


Figure 3. Schematic diagram of flexible CIGS solar cell

Flexible CIGS can use different substrates. The performance and efficiency of the device vary with the substrate. Therefore, the choice of the flexible substrate is essential, and the following factors must be considered: (1) Cost (2) Thermal stability and thermal expansion coefficient. (3) Chemical stability and vacuum stability. Researchers have tried fabricating flexible CIGS using various substrate materials, including molybdenum foil, titanium foil, and stainless-steel foil. In general, the substrate materials of flexible CIGS are mainly divided into metal and polymer [11].

2.2.3. Cadmium telluride (CdTe) thin-film solar cells

Due to its successful industrialization, CdTe thin-film solar cell is the most successful thin film solar cell. It has the following advantages: (1) The theoretical conversion efficiency is high. (2) The absorption coefficient of CdTe is high. (3) The temperature coefficient is low. For this reason, its output power is not affected by temperature. (4) The emission of heavy metals in the life cycle is low. (5) The production cost is low. Due to the simple preparation process and low cost of raw materials and equipment, the component cost of the CdTe is lower than that of a crystal silicon cell under the same cumulative output [12]. Although large-scale commercial production of CdTe has been achieved since the 1990s, the market has been slow to develop, and the market share has not been extensive. In addition, due to the fatal shortcoming of highly toxic CdTe, its research and development value and application scope are affected [4].

Chengdu ZhongBuilding Materials Photoelectric Material Co. LTD shows a cadmium telluride thin film solar cell and its optimized post-treatment method. The invention's cadmium telluride thin-film solar cell has low toxicity, low environmental configuration requirements and small maintenance cost. This invention dramatically improves the efficiency and performance of solar cells [13].

2.2.4. Gallium arsenide (GaAs) thin-film solar cell

The compound of gallium and arsenide is a semiconductor material. GaAs material synthesized by a scientist named Goldschmidt was first reported in 1929. However, Welker, a German scientist, discovered that GaAs had the electrical properties of a semiconductor in 1952 [14]. Furthermore, gallium arsenide (GaAs) thin-film solar cell has the highest conversion efficiency, up to 42%. It is an ideal material for the photovoltaic panel of the lunar rover due to the advantages of ample development space, wide band gap and high-temperature resistance. However, Ga is relatively scarce. As is toxic and has a high manufacturing cost. For this reason, its development is limited. It is not suitable for large-scale civilian production. However, it is primarily used in space stations. In addition, GaAs has been used as the world's primary power source for space flight. The proportion of GaAs modules is gradually increasing [4].

With the successful preparation of single-junction GaAs, foreign researchers began to study the practice of multi-junction solar cells in the 1980s. At that time, the average efficiency of

GaInP/GaAs/Ge triple-junction cells reached 26.5% [15]. Three-junction gallium arsenite solar cells are usually composed of three sub-junctions in series, such as GaInp, InGaAs and Ge. The spectral response range covers the band of 300 ~ 1800nm, and the utilization efficiency of sunlight is high [16]. The three-junction GaInP/GaAs/Ge solar cell, whose batch production efficiency is 30%, has entered the engineering application stage. It meets the energy needs of satellites, deep space exploration and multifunctional space transportation systems [17].

In addition, four-junction solar cell is composed of four P-N junctions in series. Compared with the structure of three-junction solar cells, there are two intermediate cells in addition to the top and bottom cells [18]. The change of material characteristics improves the absorption of the solar spectrum and the matching of the solar spectrum. The photoelectric conversion efficiency of the four-junction solar cell can reach more than 34% [19]. The gradient buffer layer technology is used in solar cells to reduce the influence of defects caused by lattice mismatch on cell performance. Compared with the existing three-junction gallium arsenide solar cells used in space, the four-junction solar cells use lattice mismatch materials. Furthermore, new technologies such as lattice epitaxial growth, bonding and stripping are used in the process implementation.

3. Reduction of the amount of lunar dust near solar PV panels

The harsh environment on the moon's surface leads to the rock powder and then a layer of lunar soil formed. Lunar dust is the lunar soil particles with a diameter of less than 1 mm. Lunar dust is suspended on the surface of the moon due to natural phenomena such as meteors and micrometeor crystals colliding with the lunar surface. Lunar dust has intensely simulated, especially easy to adhere to electrical instruments. Once it touches the surface of the solar cells of the lunar rover, it will stick to it, weakening the transmittance of photovoltaic glass and hindering the improvement of the photoelectric conversion efficiency of solar cells. As an energy device, solar photovoltaic cells are critical in the regular operation of the lunar rover. This paper summarizes five methods to improve the photoelectric conversion efficiency of the lunar rover by reducing the amount of lunar dust in contact with solar cells, such as lowering lunar dust raising, blocking the transmission of lunar dust, weakening the deposition of lunar dust, inhibiting the attachment of lunar dust, removing lunar dust accumulation [19]. Moreover, receding lunar dust deposition, inhibition of lunar dust adhesion, and briefly describing their advantages, disadvantages, and applications.

3.1. Reduce lunar dust raising

(1) The appropriate activity space and time.

Through using the circumlunar satellite to observe and understand the lunar surface environment, the landing site is initially selected, and the fundamental characteristics such as soil thickness and looseness is studied. To reduce the impact of dust generated during the movement of the lunar rover on the conversion efficiency of solar photovoltaic panels, the site with a compact and thin soil layer is selected as the landing site and the active area of the lunar rover. At the same time, there are many sizeable lunar dust storms on the moon during the morning and evening, so it is necessary to avoid lunar rover activities.

(2) Transformation of the activity environment.

The regular activity route of the lunar rover should be compacted or solidified to reduce the influence of lunar dust raised by human activities [20]. Nevertheless, this method requires a lot of energy and is not feasible to play a valuable role.

(3) Appropriate speed to move the lunar rover.

Through discrete element simulation analysis of the lunar dust [21] raising process of the lunar rover wheels, when simulated, the lunar rover drove at speeds of 0.5m/s, 1.0m/s, 1.5m/s and 2.0m/s. It was found that the lunar dust raising direction was opposite to the driving direction, and the higher the speed, the higher the moon dust raising height and the greater the impact. At present, the general

speed of the lunar rover is 0.55m/s. When the speed exceeds 1.5m/s, the dust height will exceed the height of the lunar rover.

(4) A suitable gear wheel for the lunar rover.

The activity of the lunar rover caused the rise of lunar dust, which Song Zhongliang found. Lunar soil flow momentum = Total wheel settlement - Compaction. Lunar soil flow momentum = The amount of settlement outside the two sites - The amount of compaction [22]. However, the concave wheel raises less lunar dust and impacts the solar photovoltaic panel less. Therefore, in the design of the lunar rover, concave wheels can be considered to reduce the rise of lunar dust and promote the photovoltaic conversion efficiency of solar energy.

3.2. Block the transmission of lunar dust

The spreading process of lunar dust can be blocked and the amount of lunar dust contacting the panel can be reduced through installing a device around the solar photovoltaic panel.

(1) Automatic dust cover.

The automatic lunar dust machine can cover the surface of solar photovoltaic panels. When solar panels need to work, the lunar dust cover opens automatically; when the power is enough, lunar rover dormancy, the lunar dust cover shuts down automatically, thus weakening the lunar dust's influence on the photovoltaic panels, reducing the phenomenon of the adhesion of lunar dust when the solar panel does not work. Nevertheless, it cannot use when solar photovoltaic cells are working, and the mechanism is prone to malfunction.

(2) Dust shield.

The dust shield can block the movement of lunar dust so that the raised lunar dust cannot contact the solar photovoltaic panel.

3.3. Recede lunar dust deposition

(1) If conditions permit, the angle of the solar photovoltaic panel should be set as large as possible to reduce the deposition of lunar dust.

(2) Neutralization method:

After the photoelectric effect, solar irradiation effects of lunar dust will be charged, and the long float moves, put the alpha particle source near solar photovoltaic panels, use it to make the lunar dust surrounding take positive, and place negatively charged plate near the photovoltaic panels, due to the positive and negative charges attract each other, positively charged lunar dust adsorption, and positive and negative charges are neutralized, lunar dust falls from the adsorption plate on the solar photovoltaic cell to the lunar surface [20].

3.4. Inhibition of lunar dust adhesion

(1) The micro-texture on the surface of photovoltaic cell glass [23]:

The hydrophobic principle of the lotus leaf and the bionic leaf surface can resist pollution and have a tremendous self-cleaning ability to protect the surface of solar photovoltaic cells and reduce the influence of lunar dust. The micro-texture on the surface of lunar rover photovoltaic glass is a columnar protrusion with a specific shape and regular arrangement. Such a structure can significantly reduce the contact area between lunar dust and solar photovoltaic panel, thus inhibiting the attachment of lunar dust. Figure 4 shows SEM morphology of the microtextured side of the glass surface. Figure 5 shows diagram of contact between moon dust and battery surface.

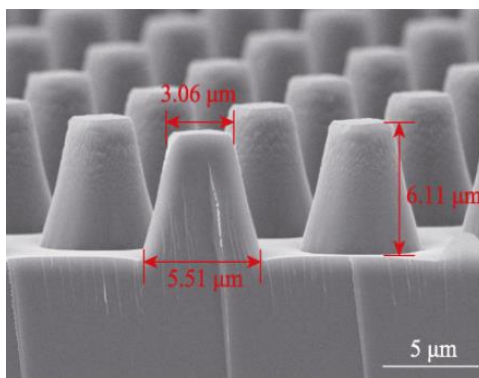


Figure 4. SEM morphology of the microtextured side of the glass surface [23]

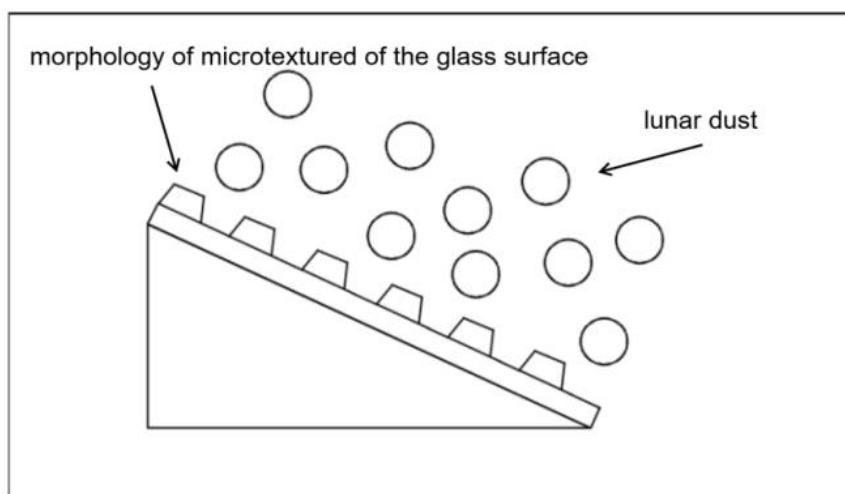


Figure 5. Diagram of contact between moon dust and battery surface

JQ Li et al. studied the deposition of lunar dust amount by observing the micro texture on the photovoltaic glass surface and found that the micro-texture of regular hexagons showed the most vital self-cleaning ability [23]. When the amount of lunar dust was 3g, 5g and 7g, the self-cleaning ability of micro-texture of different shapes decreased firstly and then increased [24]. This result shows that applying micro glass texture on the surface of solar photovoltaic cells should also be used with dust prevention measures to control the amount of surrounding lunar dust to achieve the best effect of suppressing lunar dust to promote the role of photovoltaic cells and improve the photoelectric conversion efficiency.

(2) Conductive film plating [20]:

Plating an ultra-thin conductive film (such as indium tin oxide film) on the surface of the solar photovoltaic panel can promote the effective photoelectric conversion of the photovoltaic cell. Plating a conductive film on the surface of the device is easy to operate and does not generate additional energy consumption.

3.5. Remove lunar dust accumulation

When lunar dust prevention measures cannot play a full role, it is necessary to take adequate measures to remove the lunar dust accumulation to ensure the regular use of solar photovoltaic cells.

(1) Vibration dust removal:

The vibration device which has appropriate frequency and amplitude occupies a small space, has a small mass and is convenient to arrange, but it also produces energy consumption.

(2) Electric curtain dust removal:

"Electric curtain dust removal" means that transparent electrodes (conductors) are connected to a single phase (or polyphase) AC power supply in parallel to form an electric curtain [25]. After being energized, generate the alternating moving electric solid field. Through the polarization of the strong electric field, the lunar dust will be lifted by the electric field force and move perpendicular to the

axis direction to achieve the removal of lunar dust. The advantages of this method are that it can be easily used outboard, does not need to move the device, can be well applied to the surface of solar photovoltaic cells, has high dust removal efficiency, which can be up to 80%~90%, and only need to have a quick and fast removal when the lunar dust is up to a certain amount. However, the electric curtain dust removal is prone to be out of order. Figure 6 shows the basic structure of the electric curtain.

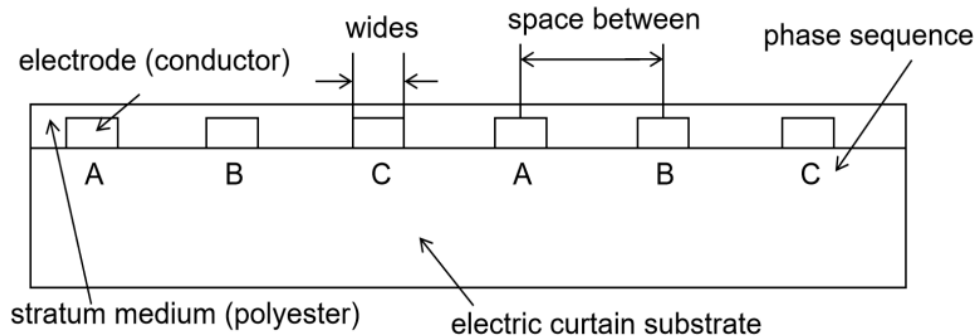


Figure 6. The basic structure of the electric curtain

(3) Mechanical cleaning

A special brush can be used to clean lunar dust, such as the nylon brush to remove coarse particles of lunar dust. Although the brush can overcome the adsorption force between dust and surface, and it has a cleaning effect, the dust is difficult to be removed, which leads to a poor cleaning effect. Therefore, it needs consumes a lot of physical energy and time, and the cleaning process may damage photovoltaic panels and the device's everyday use.

(4) Vacuum cleaner

A vacuum cleaner, like a household vacuum cleaner, is used to remove dust on the surface of the photovoltaic panels by inhaling air and dust through solid force and then blowing out the air after filtering. This method has high efficiency but also high energy consumption. Moreover, the device may be blocked by inhaling foreign bodies, affecting its use.

4. Solar panel design for tracking solar energy

With development of an essential product of aerospace, the lunar rover has always been concerned about its energy supply. In the harsh conditions of the moon, solar energy is the best option today due to its renewable and ubiquitous property. However, due to the poor continuity of its energy reception, susceptibility to environmental factors, and low energy density, the collection and utilization of solar energy have always been low. Therefore, improving energy collection and conversion efficiency has become an urgent problem to solve. As an essential device to provide the required energy for the lunar rover, the rational design of solar panels is crucial.

4.1. Insolation efficiency of solar panels

The intensity of the light depends on the number of photons X . Furthermore, the light energy received by the solar panel at a particular moment is equal to the sum of the energy carried by all the photons incident on the solar panel at that moment [26]. If the photon density in the light field is A , the area of the solar panel is B , and the angle between the incident direction of the sunlight and the panel is θ , then the actual number of photons incident on the panel is x .

Under ideal conditions, the number of photons incident on the windsurfing board is x_0 , and the solar windsurfing board's insolation efficiency is $x_0/x = \cos\theta \cdot 100\%$.

By calculating the sun exposure efficiency, the magnitude of the exposure efficiency depends on the angle between the incident angle of sunlight and the sailboard. When the angle is 90° , the exposure efficiency is one. Therefore, it is possible to continuously adjust the angle between the incident

direction of the sunlight and the windsurfing board to improve the insolation efficiency of the solar windsurfing board, thereby improving the utilization rate of solar energy.

4.2. Single-degree-of-freedom solar panel drive mechanism

The single-degree-of-freedom solar panel performs a single-degree-of-freedom rotational motion around the hinge of the lunar rover body. Due to this driving mechanism's limitation of space geometry, it can only change the angle between the windsurfing board and the incident angle of sunlight in one plane. Therefore, this mechanism has poor directivity to the sun, the average direction of the windsurfing board is significantly different from the incident direction of sunlight, and the sun exposure efficiency is low. Therefore, to improve the absorption of light energy by the windsurfing board per unit time, it is necessary to improve the driving method of the solar windsurfing board. Figure 6 shows Schematic diagram of the single-degree-of-freedom solar panel mechanism.

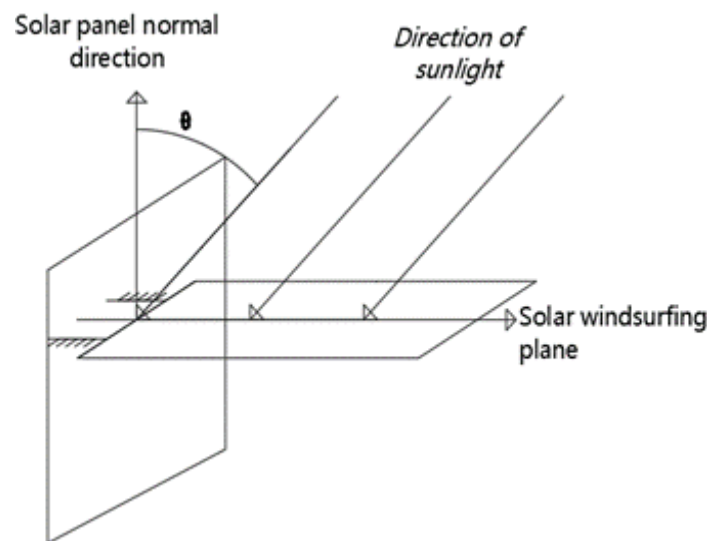


Figure 7. Schematic diagram of the single-degree-of-freedom solar panel mechanism

4.3. Double-degree-of-freedom Solar Panel Drive Mechanism

Domestic scholars such as Tao Yi, Pan Canyon, and Tan Yingqi et al. have also proposed a new dual-DOF system for sun orientation. This paper takes this as an example to introduce and analyze the dual-DOF system's sun orientation mechanism. In this figure, the plane of the windsurfing board is parallel to the ground. When the solar windsurfing board is working, the sunlight is always above the plane of the windsurfing board. Furthermore, the driving mechanism is installed in the reverse direction in the common direction perpendicular to the geometric centre point of the windsurfing board pointing to the ground. The installation axis of the windsurfing board can be deflected around the coordinate axes OU and OV (the deflection angle can be rotated from -90° to 90°). Suppose the plane of the windsurfing board is installed perpendicular to the installation axis of the windsurfing board. In that case, the standard line of the windsurfing board can be oriented in any direction in the space above the UOV, thereby accurately orienting to the sun. This mechanism also avoids the 360° rotation of the windsurfing board around the car body, thus avoiding using a Slip-ring, which reduces the system's reliability [27]. Based on the above analysis, it can be concluded that the two-degree-of-freedom sun-directed mechanism is superior to the single-degree-of-freedom sun-directed system in terms of sun-directed accuracy. Figure 7 shows schematic diagram of a two-degree-of-freedom solar windsurfing panel.

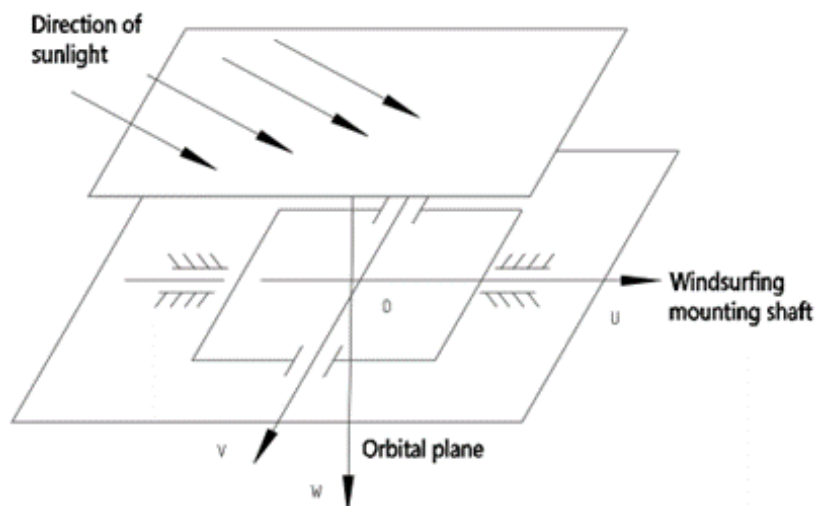


Figure 8. Schematic diagram of a two-degree-of-freedom solar windsurfing panel.

4.4. The control method is its characteristic

The control methods of the solar panel mechanism are divided into three categories: open-loop control, closed-loop control, and semi-open-loop control. Open-loop control mainly uses a stepper motor to drive the movement of the windsurfing board. This method depends on the manufacturing precision and uses the environment of the stepper motor. Therefore, the error is significant. In closed-loop motion, the sensor measures the motion parameters of the working plane of the mechanism and changes in the external environment. It feeds the measured values back to the processing system. The processing system sends a control signal to the controller according to the feedback value and then drives the motor to complete the predetermined action through the amplifying circuit, etc. This method has high precision and is mainly used on high-precision occasions. In the semi-closed loop system, the sensor directly measures the parameters of the motor output shaft, sends the parameters of the motor shaft to the sensor, and then passes through the amplifying circuit conversion circuit to control the motor to move. This article will mainly introduce the design method of a closed-loop system.

The hill-climbing tracking principle: With the constant change of the incident angle of sunlight, the energy received by the photovoltaic panel will also change accordingly, which will cause the output voltage of the photovoltaic panel to change [28]. However, simultaneously, the photovoltaic panel will always have a position with the highest voltage output. This paper shows that the sun exposure efficiency is related to the incident angle of sunlight. At this time, the best position of the solar sail panel can be determined by detecting the output voltage value of the photovoltaic panel, and the height angle and direction angle of the sail panel mechanism can be adjusted continuously. When the read voltage value is the global peak value, get the incidence of sunlight currently. In theory, the light should be perpendicular to the layout of the photovoltaic panel, and the tracking will be stopped at this time. There is no cumulative error in the hill-climbing method tracking. The disadvantage is that when the intensity of sunlight changes significantly in a short period, it may cause misoperation of the actuator, thereby affecting the tracking accuracy. When the output voltage value of the photovoltaic panel is greater than the set value, the mountain climbing tracking is carried out to save the read voltage value. After pushing the photovoltaic panel to a certain Angle, the current-voltage value is read and compared with the voltage value saved before the rise. If it exceeds the voltage value before the rise, the photovoltaic panel will continue to rise. Otherwise, the push rod will push the photovoltaic panel down at a certain angle. When the photovoltaic panel drops by a certain angle, read the current voltage value, and compare it with the voltage value before the drop. If it exceeds the voltage value before the drop, the photovoltaic panel will continue to drop. Otherwise, the motor will rotate forward. By continuously adjusting the push rod and comparing the voltage values, the sun altitude angle tracking is completed, and the azimuth angle tracking principle is the

same as above. It is calculated that the hill-climbing tracking method can increase the power output by about 32% compared with the fixed installation method, which effectively improves the conversion power of the photovoltaic panel. That is a better control method theory.

5. Conclusion and Future Aspects

This paper mainly describes three ways to improve the efficiency of solar photovoltaic conversion (Select thin film solar cells with high radiation resistance and conversion efficiency, reduce the amount of lunar dust on photovoltaic panels, and choose solar panels with higher degrees of freedom). There are four main types of thin-film solar cells based on the current commercialization of solar cells, (1) silicon-based thin film solar cells, (2) Copper indium gallium selenium (CIGS) thin film solar cells, (3) Cadmium telluride (CdTe) thin film solar cells, (4) gallium arsenide (GaAs) thin film solar cells. Among the four cells, the gallium arsenide thin film solar cell has the highest conversion efficiency, its development space is ample, the gap width is significant, and it is also high-temperature resistant, so it is an ideal material for lunar rover photovoltaic panels. On the other hand, after the improvement of the multi-junction, the efficiency is greatly improved and even close to the highest conversion efficiency. Therefore, multi-junction gallium arsenide thin film solar cells should be used as far as possible to obtain energy in the lunar vehicle. The part of reducing the amount of lunar dust is mainly to introduce the amount of lunar dust in contact with the lunar rover and the method of removing lunar dust. The moon rover has many delicate structure designs, but it is too energy-intensive and inefficient to use active removal.

Moreover, the circuit device design adds more complexity to the creation of the lunar rover, making removing lunar dust more difficult. Combined with the current measures to reduce the amount of lunar dust near solar photovoltaic cells, it still needs to focus on protection and take various actions to reduce the adsorption and deposition of lunar dust to improve the efficiency of photovoltaic conversion of solar energy. If necessary, appropriate measures should be taken to remove the deposited lunar dust in time, to ensure the solar photovoltaic conversion efficiency of the lunar rover, as well as the usual activities and work of the lunar rover. For the design of solar panels, this paper compares the structure of single and double DOF solar panel, clarify the advantages of the double DOF solar panel mechanism, and propose the control mode of the solar panel mechanism (mountain climbing tracking method).

Technological advances have continuously progressed; many advanced materials and technologies are emerging endlessly. In the multi-junction process of GAAS film cells, the preparation of four junction gallium arsenide film cells has been started. In today's continuous human exploration of space, the technology will further improve the energy conversion efficiency of the solar wing. Furthermore, it can improve the carrying capacity of the star without changing the configuration and mass of the solar wing. In terms of lunar dust reduction, constantly improve the protection measures, reduce the use of energy consumption, and improve the protection and removal efficiency. In the aspect of solar panel design, advance the research and wide application of the dual degree of freedom-oriented mechanism to the sun, the efficiency of solar photovoltaic conversion will also be improved to ensure the activities of the lunar rover and promote the development of human lunar exploration.

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