Research Article

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Computer-aided measurement technology for Cu_2ZnSnS_4 thin-film solar cell characteristics

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Abstract: Currently, there are more perfect theoretical basis and operation methods for the research of the Cu_2ZnSnS_4 (CZTS) solar cell characteristics, but the experimental process is tedious. In this article, to measure the characteristics of the CZTS solar cells more accurately and quickly, the computer-aided measurement method was used. During testing the characteristics of solar cells, the results were collected and analyzed by using LabCoder and Origin software. By designing experiments and using software to record data and complete solar cell characterization tests in one step, the number of artificial changes in resistance during testing is reduced. In the experiments, the data can be obtained in real time by using experimental results of computer-aided measurement technology, which can significantly improve the experimental efficiency. Through computer real-time monitoring, the maximum output power of as-prepared solar cells is $P_m = 1.62$ W, and the calculated filling factor remains at 86%. It means that computer-aided measurement technology is suitable for the experiment of CZTS solar cell characteristics.

Keywords: solar cell, battery experiment, computer-aided measurement method, fill factor, Cu_2ZnSnS_4

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1 Introduction

In the twenty-first century, solar energy is considered as one of the most perfected new energy for developing a resource-efficient society [1–4]. Solar cells come into being and have emerged as a key part of the new solar energy sector. Among solar cells, thin-film solar cells have been the focus of many researchers due to their high-photovoltaic conversion efficiency and low cost. The most important parameter of thin-film solar cells is the photovoltaic conversion efficiency, which is affected by the properties of the coating material [5–7].

In recent years, the majority of thin-film solar cells use semiconductor material as a surface coating [8]. Nevertheless, semiconductor materials are expensive and will endanger the health of production personnel [9–11]. On contrary, Cu_2ZnSnS_4 (CZTS) possesses the advantage of being low cost and nonpolluting, as well as an excellent bandgap (1.4–1.5 eV) and absorption coefficient (10^4 cm^{-2}) [12]. It is obtained by replacing iron with tin and zinc based on $CuFeS_2$ [13–15].

So far, different methods are used to analyze and research the characteristic of CZTS solar cells. The most common method is to illuminate the photovoltaic device with a Xenon lamp and collect data of solar cells through the electronic load [16–18]. Li *et al.* prepared a CZTS thin-film solar cell, which was based on oxygen-containing precursors. It was tested using a solar simulator (NEWPORT) as the light source and a KEITHLEY 2400 digital source meter [19]. Similarly, Long *et al.* formed CZTS films by the sol–gel method following sulfurization. The characteristics of the CZTS thin-film solar cell were recorded by a KEITHLEY 2400 source meter under an illumination intensity of 100 mW cm^{-2} [20]. By using MP-3005D as the power source, Panahi-Kalamuei *et al.* [21] tested the efficiency of synthesized solar cell devices and changed the irradiation power to achieve a filling factor of 65%.

However, in the research of CZTS solar cell characteristics, the processing of experimental data is time-consuming. During the experiment, the output power associated with the resistance cannot be adjusted in time, and the data from the electronic load need to be calculated and analyzed by manual work [22–24]. To research the characteristics of solar cells more accurately and speed up the experimental process, computer-aided measurement technology is introduced into the experimental process.

In this article, based on the photovoltaic effect, the experiments were designed to test the characteristics of CZTS solar cells. The experimental data were collected by LabCorder software and analyzed in real time by Origin. By connecting LabCorder software to the resistor and setting its logic for processing data, the experimental data can be obtained by simply adjusting the resistor during the experiment. It optimized the traditional experimental process of adjusting the resistance value and recording the data several times. The important variables, such as output current, output voltage, and fill factor value of CZTS solar cells, were obtained through the experiment by Origin. All results are processed by computer, thus reducing the human work and saving a lot of time. Finally, the characteristics of the solar cell were intuitively explored by analyzing the data obtained from the solar energy conversion test, and the difference between the actual power of the solar cell and the theoretical power was investigated.

2 Experiment of CZTS solar cell characteristics

2.1 Experimental principle of CZTS solar cell characteristics

The experimental principle of testing solar cell characteristics used in this study is based on the photovoltaic effect. It can be explained that the p–n structure of the semiconductor will change when the solar cell receives natural light, in which the electronic potential field is produced at both ends during the electrons transporting from the P-end to the N-end. After being irradiated by natural light, the electrons can be transported continuously, thus generating the potential energy of the electric power to output and storing this part of electric energy. In the experiment of CZTS solar cell characteristics, it is necessary to obtain the important parameters of output current, output voltage, the filling value FF of the solar cell, and so on [25].

Moreover, the electrons are transported from the P-end to the N-end when the solar cell is irradiated by natural light so that a current flowing from the N-end to the P-end is generated in the solar cell, which is labeled as I_1. At the same time, a forward current opposite to the photovoltaic current will be generated, in the process of the photovoltaic current generation, so this current is marked as I_2. Consequently, the photovoltaic output I is defined as the difference between the two kinds of current. The specific calculation equation of current I is as follows:

$$I = I_1 - I_2 = I_1 - I_0\left[\exp\left(\frac{qV_D}{nk_BT}\right) - 1\right], \quad (1)$$

where I_0 is the reverse saturation current generated by natural light irradiation, and V_D is the actual pn junction voltage. I_1 is the photovoltaic current, whose value is directly proportional to the intensity of light, and its photoelectric conversion efficiency is affected by the material characteristics and the actual structure of solar cells. n is called a characteristic coefficient, which is determined by the pn structure characteristics, and its value is the theoretical value, usually in 1–2 [26,27]. T is the standard thermodynamic temperature, Q is the electron charge generated by lighting, and k_B is the Boltzmann constant.

Under special circumstances, if the series resistance of solar cells can be neglected, the V_D can be expressed as the actual voltage V of the solar cell. Then, the actual equation is shown as follows:

$$I = I_1 - I_2 = I_1 - I_0\left[\exp\left(\frac{qV}{nk_BT}\right) - 1\right]. \quad (2)$$

In the case of the solar cell-forming loop, the cell will generate a short circuit, the voltage will turn to 0, and the output current is the actual current. According to Eq. (2), the short-circuit current I_k can be expressed as follows:

$$I_k = I_1. \quad (3)$$

Moreover, the current generated by the amount of photovoltaic is equal to that of the actual current in the case of a short circuit. And its value depends on light intensity and photoelectric conversion efficiency [28]. Therefore, calculating the current generated by photovoltaics is an ideal method to obtain the limit state current.

When the output end of the solar cell is opened and the circuit is cut off, no current is generated in the circuit, so the actual current I generated by the solar cell is 0 [29]. In this case, the obtained voltage is defined as open-circuit voltage V_0, which can be expressed as follows:

$$V_0 = \frac{nk_BT}{q}\ln\left(\frac{I_k}{I_0} + 1\right). \quad (4)$$

Generally, there is an extra load resistance R existed in the solar cell, whose value varies from 0 to infinity. It is indicated that the existence of load R will affect the output power of solar energy [30,31]. Ideally, the output power of the solar cell is deemed as the maximum power when the load R is at the optimal value, which is marked as P_m. The equation is as follows:

$$P_m = I_m V_m. \quad (5)$$

The I_m and V_m in the equation are the output current and the output voltage in the limit state, respectively, whose product represents the optimal output power P_m. The value obtained by dividing the product of voltage and cutoff current in an open circuit by the optimal output power P_m is the fill factor, which is marked as FF. The related equation is as follows:

$$\mathrm{FF} = \frac{P_m}{V_0 I_k} = \frac{V_m I_m}{V_0 I_k}. \quad (6)$$

The fill factor FF is an important parameter for measuring the characteristics of solar cells, especially the conversion efficiency of solar cells. The larger the value of FF, the higher the corresponding output power, and *vice versa*. Therefore, the value of FF is the main basis for judging the characteristics of solar cells at present [32]. It is confirmed that the value of FF will be affected by various factors, such as light intensity, structure and conversion efficiency of coating material ideal coefficient, and resistance value [33,34]. In addition, it can be found from the equation that the short-circuit current I_0, open circuit voltage V_k, optimal current I_m, and optimum voltage V_m are the other main factors that affect the value of the filling factor. Therefore, based on these values, an experiment on the characteristics of CZTS solar cell is designed, and the conclusion of solar energy characteristics research is drawn.

2.2 Experimental contents of CZTS solar cell characteristics

The solar cell characteristic instruments commonly used in experiments include an ammeter, voltmeter, and test load. More precise instruments should be used as far as possible in the experiment, and ordinary ammeters and voltmeters can be used instead of a digital multimeter. While the load is replaced by an adjustable precision resistor, the accuracy of the test results can be improved. Furthermore, the adjustable resistor can be precisely adjusted to the required resistance value for the test, while providing more accurate data in the experiment and eliminating the problems caused by load changes. The concrete schematic diagram is shown in Figure 1.

In the experiment of solar cell characteristic measurement, it is necessary to put the solar cell under natural light with a certain intensity and then record the corresponding current and voltage values when the load value changes from small to large or from large to small, to find the best load value, as well as the best current value and voltage value. However, due to the tedious operation process and the need for multiple adjustments to obtain the best value, this manual calculation method is quite time-consuming. On the contrary, by collecting data and using computers for statistical analysis, the calculation results can directly reflect the required data, greatly reducing the workload.

3 Computer-aided measurement technology is applied to the experiment of CZTS solar cell characteristics

Origin is a kind of computer data processing software that specializes in dealing with such measurement problems. In the experiment of CZTS solar cell characteristics by computer-aided measurement, data collection is carried out in conjunction with LabCorder software, by which the data can be collected and input into the computer in real

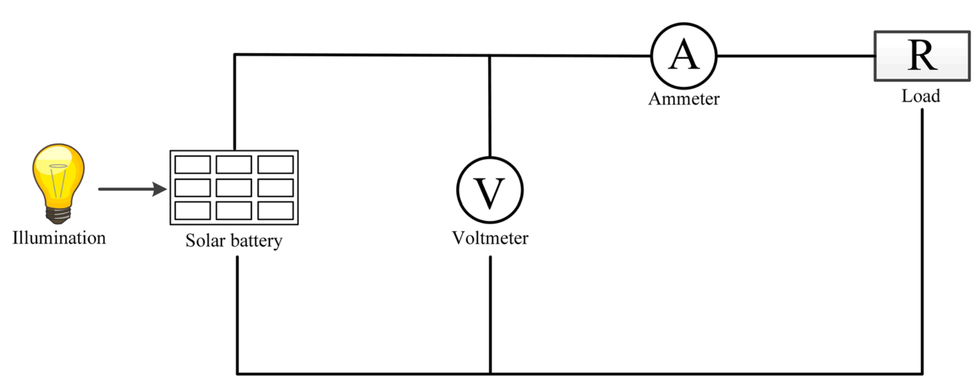

Figure 1: Theoretical experimental method for solar cell characteristics.

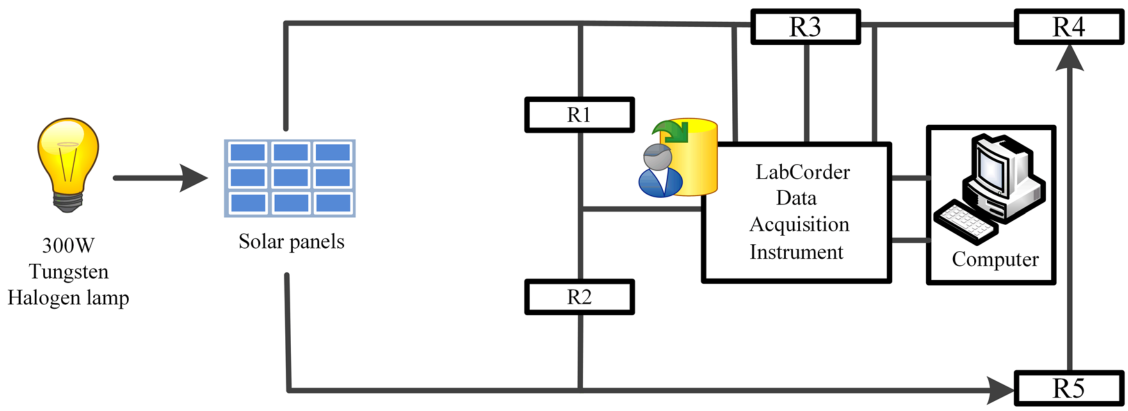

Figure 2: Data acquisition circuit of CZTS solar cell.

time. After dynamic processing of data, it can accurately reflect the characteristics of the solar cell. LabCorder data acquisition system has multiple functions. It integrates an experimental data collector, calculator, and data analysis system and can process data after collecting data, and then output results, which is a professional instrument designed for this kind of experiment.

In the function of LabCorder, the input analog signal was in the range of −5 to 5 V, and the amplitude of the input signal can be adjusted and changed with a multilevel signal amplification utility, to ensure the accuracy of the signal conversion function.

In the process of the experiment, the fixed light intensity was used to simulate the natural light, and the halogen tungsten lamp holder was used. The power of the lamp was 300 W. Taking two fixed values as references, the output voltage of the solar cell was detected, and the resistance values were all 100 Ω. In the process of exploring the load current, a precision adjustable varistor was used as the regulating source. The fixed value resistor and the adjustable varistor were, respectively, connected to the one and two input channels in the LabCorder data collector. At the same time, to adjust the output current, the resistor with large resistance was accessed on the mainline, for limiting the too large current, preventing burning equipment. The large resistance resistor adopted the line resistance with a maximum of 420 Ω. But this was not enough to load current for fine adjustment, and it was necessary to add a resistor with small resistance, a line resistance whose maximum resistance was 56 Ω based on the large resistance resistor to fine tune the current. After this circuit was completed, testing of the CZTS solar cell can be started. The specific circuit is shown in Figure 2.

In Figure 2, R1 and R2 were the 100-Ω resistors with a fixed value, R3 was the adjustable precision resistance box, R4 was a line resistance with a maximum of 56 Ω, and R5 was the line resistance with a maximum of 420 Ω. After the circuit was closed, the lamp source was turned on, and the lamp source angle was adjusted so that the voltage value of the segment R2 was between 4.5 and 4.9 V. Before the adjustment of light source angle, resistance R4 and R5 were adjusted to 0 Ω, after the adjustment of light source angle, the adjustable precision resistance box was to adjust so that the voltage value of segment R3 was less than 5 V. Then, the magnification of the LabCorder data acquisition instrument was adjusted, and the output value was more obvious.

After LabCorder data collector was adjusted, the next step was to input LabCorder data to process logic. The overall change function was set in the relationship between *y* and *x*, where the *y* end interface took the segment R3 interface, and the *x* end interface took the segment R2 interface. After both ends of the set were complete, the device was switched on, and then, R4 and R5 were pulled from the minimum to the maximum at a steady speed. From the change of resistance value, the small-to-large change curve can be obtained. This process can simulate the dynamic voltage changes of solar cells under fixed light intensity and obtain the change curve at the output end of the LabCorder interface.

The data from the x and y end interface collected by LabCorder can be input into Origin data processing software after simple logic processing, and the exact data changes can be obtained from the data. After the fine processing, the data can be transformed into the current value and voltage value generated by the CZTS solar cell, so that the curve can be accurately drawn and the change in the characteristics of the solar cell can be found. After actual calculation, the specific data changes are shown in Figure 3.

Based on Figure 3, the power changes under specific conditions can be seen more intuitively. First, when the line is in a short circuit state, the load voltage is 0 and the generated short circuit $I_k = 0.19$ A at this time. At the same

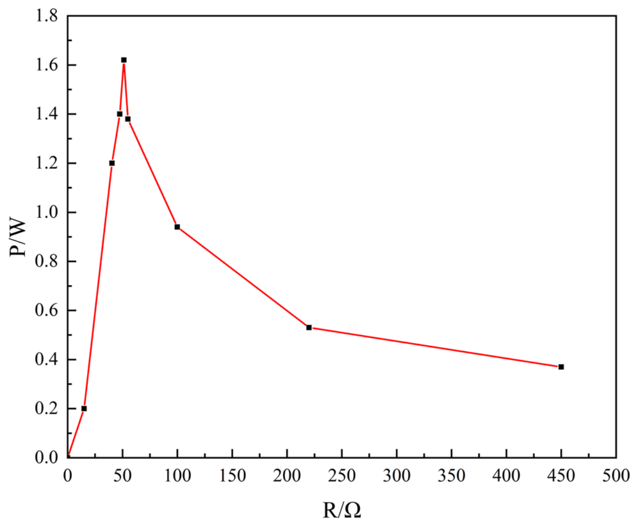

Figure 3: P–R influence table for CZTS solar cell.

time, when the line is cut off, the load current is 0, and the open-circuit voltage is V_0 = 9.92 V. According to the data shown in the table, the trend of overall power under dynamic load discovery is obtained, and then, the optimal power point of CZTS solar cell characteristic curve is found. In the trend curve of the chart, it can identify the highest powerpoint. When at the highest point, the load resistance is 51.3 Ω, then the output power of the solar cell is P_m = 1.62 W. According to the numerical point of P_m, the corresponding current and voltage conditions can be found, and the following conclusions can be drawn: I_m = 0.19 A, U_m = 8.532 V. Finally, according to Eq (6), the value of filling factor FF = 0.860 is obtained.

4 Result analysis

After monitoring the characteristics of the CZTS solar cell, the FF value of the solar cell is 0.860, which indicates that the photoelectric conversion efficiency of the solar cell is excellent. In the course of the experiment to explore the solar cell characteristics, the computer is used as a tool to assist measurement, making the process more scientific and standardized, and the data are more accurate, which can withstand scrutiny theory [35]. Through the use of computer data acquisition and data processing systems, data acquisition work will be carried out more smoothly. It can collect more data, and the accuracy of the data can be fully guaranteed. After connecting to the data processing system, the overall experimental process will be clearer. In this process, the data feedback is fast, and the real-time data are accelerated with the experimental progress, which accelerates the experimental process and greatly reduces the experimental steps. In the previous experiment, the instrument is adjusted according to the experimental principle [36]. The result is calculated according to the change of the previous experiment. Meanwhile, the process of the conclusion is simplified and the computer is responsible for all the results, thus reducing human work and saving a lot of time.

5 Conclusions

The computer-aided measurement technology was used in the investigation of the characteristics of CZTS solar cells, and the obtained data are analyzed by Origin software. The main parameters of the CZTS solar cell, such as the generated short circuit (I_k = 0.19 A), open-circuit voltage (V_0 = 9.92 V), peak current (I_m = 0.19 A), peak voltage (U_m = 8.532 V), and peak power (P_m = 1.62 W), were obtained quickly and accurately with the aid of computer technology. The analysis and research on the characteristics of CZTS solar cells by computer-aided measurement technology can make the experimental process more efficient and accurate. During the experiment, the FF value (FF = 0.860) of the CZTS solar cell needs to be obtained by calculation. The method of getting FF values can be more convenient and faster by editing the formula in Origin.

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