The study on the method of monochromatic light photon flux density converting to standard solar illumination used for silicon cell hydrogenation

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In order to detect the monochromatic light intensity during the hydrogen passivation process for silicon solar cells, a method was developed to measure and convert the photon flux density data of the monochromatic light to the standard solar irradiation. Meanwhile, a test device was designed based on Freescale ARM Micro-controller. A standard solar cell chip was used as a detector, the acquired signal will be converted to standard solar illumination and the result will be shown on the OLED screen finally. The experiment showed that the device can precisely test the monochromatic light photon flux density.

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1. Introduction

In recent years, solar cell has been one of the most important research directions in new energy field 0. And the light induced degradation (LID) of silicon cells is continuously concerned since discovered by H. Fischer [2] in 1976. The mechanism of LID of P-type boron-doped silicon solar cell was explained by Schmidt in 1997 [2]. The theory demonstrated that in conditions of light illumination, B-O complex with the ability to combine the minority carriers would be generated by boron and oxygen, reducing the minority carrier lifetime, thus reducing the efficiency of the solar cell [2]. In order to overcome LID, deep researches in raw materials and fabrication processes were carried on in the last few years, especially the hydrogen passivation technology.

During the process of hydrogen passivation, large numbers of electron-hole pairs are generated under the condition of high-intensity light irradiation and heating, which will combine the H element and cause different charge states of H, including H^0, H^+ and H^-, and most of H is verified to come from the SiN:H film deposited by PECVD(Plasma Enhanced Chemical Vapor Deposition) 0-. During the hydrogenation process, different H states will combine defects and impurities inside the solar cells. For example, B^- is combined with H^+, P^+, Fe^+, and BO^+ are combined with H^- 0-. In 2014, Brett J. Hallam from University of New South Wales, Australia, gave an irradiation to the solar cell using laser as the light source, meanwhile, applied a suitable temperature. Eventually, the open-circuit voltage increased to 680mV, the minority carrier lifetime increased from 250-500 μs to 1.3–1.4 ms 0. The result showed that the electrical characteristics of the silicon solar cell will be improved after hydrogen passivation. High intensity monochromatic light sources like laser 0 are usually used in hydrogen passivation technology.

To enhance the absorption of photons and reduce the costs of hydrogenation, high intensity LED light source may have a broad prospect. In this paper, high intensity LED of 940 nm wavelength was adopted to irradiate the solar cells, and the light intensity was continuously adjustable. In the case of solar cell, if the light source meets the spectral response range, at most one pair of carriers is produced when a photon is absorbed, no matter how high the photon energy is. Since the individual photon of infrared light has a low energy, it is not suitable to measure the monochromatic light intensity by common standard daylight optical power parameters. In this case, the photon flux density was considered to reflect the light intensity during hydrogenation and a method was developed to convert the photon flux density data of the monochromatic light to the standard solar illumination (The spectral distribution satisfied AM1.5G and the temperature was 25 ℃). Moreover, a test device was designed based on ARM Micro-controller. The experiments showed that the device can precisely detect the monochromatic light intensity.

2. Theory

The base of the silicon solar cell is a PN junction and it is able to convert light energy into electrical energy by photovoltaic effect 0. When the PN junction is irradiated with light of suitable wavelength, the electron-hole pairs are generated inside the cell. Under the action of the built-in electric field, the electromotive force is generated by the movement of the electron (to N region) and the hole (to P region).

As one of the most important parameters of solar cells, the short-circuit current can indirectly reflect the photon flux density. When the cell is irradiated by a monochromatic light, the relationship between short-circuit current and wavelength can be theoretically and approximately described as Eq.(1):

$$I_{sc} = EQE \times N_{ph} \times A \times e \qquad (1)$$

Where, *EQE* is the quantum efficiency of the cell under the irradiation of this monochromatic light, N_{ph} is the photon flux density. *A* is the area of the cell and *e* is the electron charge. Thus it can be seen that the photon flux density can be figured out, as shown in Eq.(2), corresponding to Eq.(1):

$$N_{ph} = I_{sc} / (EQE \times A \times e) \qquad (2)$$

Thus, it is obvious that the N_{ph} can reflect the monochromatic light intensity. But in order to intuitively reflect the high intensity of monochromatic light during the process of hydrogen passivation, the concept of equivalent solar illumination, which is the ratio of N_{ph} and the photon flux density of standard sunlight(AM 1.5G), is put forward in Eq.(3):

$$X(Suns) = I_{sc} / (EQE \times A \times e \times N_{ph0}) \qquad (3)$$

Where, the photon flux density of standard sunlight is expressed as N_{ph0} in Eq.(3). The photon flux density spectrum (ASTM-IEC) between wavelength of 300 nm and 1100 nm is given in Fig. 1. The integrated result of this curve is 2.89E+17 $cm^{-2}s^{-1}$, approximately equaling to N_{ph0}.

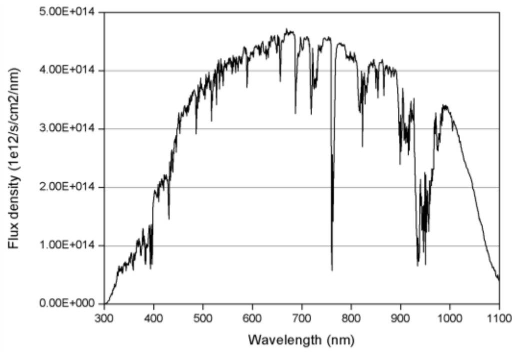

Fig. 1. Photonic flow density spectrum of sunlight (ASTM-IEC)

Fig. 2 shows the relationship between *EQE* and wavelength. Under the irradiation of 940 nm light source, the *EQE* of the solar cell we used in this paper is 74.29%. The valley in 400 nm of the curve was caused by the deviation between the conversion of two test optical gratings, but it did not make a difference because the data apart from 940 nm was not used here.

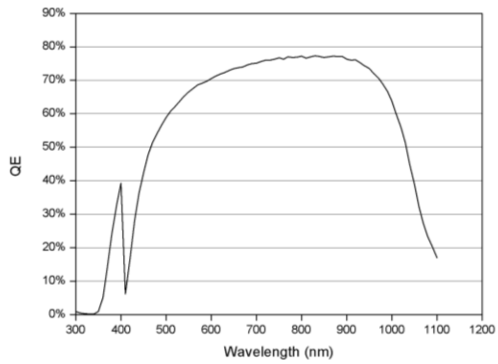

Fig. 2. QE test result of the cell

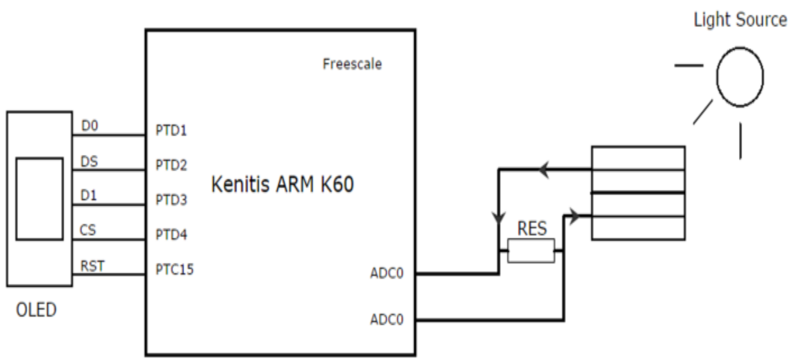

Fig. 3. Hardware block diagram of the system

3. Experimental details

3.1. Hardware design

The ARM Micro-controller produced by FREESCALE was used as the chip of the device. The hardware block diagram of the system can be seen in Fig. 3.

(1) ARM Micro-controller: 12-bit FREESCALE Kenitis ARM K60 chip with Cortex-M4 kernel, two 12-bit

ADC channels and four 32-bit timers 0 was adopted. It is suitable for situation where processing speed and accurancy are strictly required.

(2) OLED screen: made of organic light-emitting diodes, with 4-wire serial SPI interface.

(3) Sampling circuit: As the solar cell is a constant-current source essentially 0, sampling resistance was needed to convert current signals into voltage signals, then the signals were input to the AD channel of the controller. To satisfy the analog signal range, the operational amplifier circuit was used for voltage amplification, and the circuit diagram is in Fig. 4. LM2940 is a regulator chip, providing operating voltage of 5V. The -5V voltage generated by negative voltage output module was applied to OP-07 amplifier.

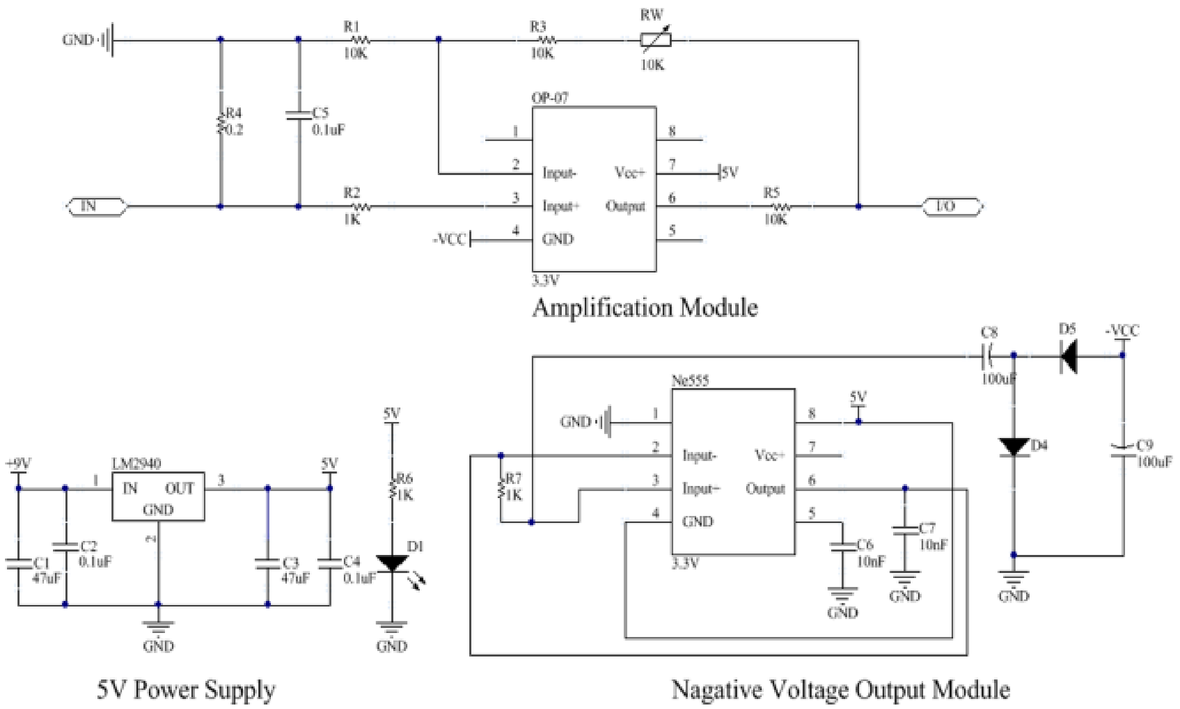

Fig. 4. Schematic diagram of sampling circuit

3.2. Software design

Fig. 5 shows the working chart of the test device, and the specific method is as follows:

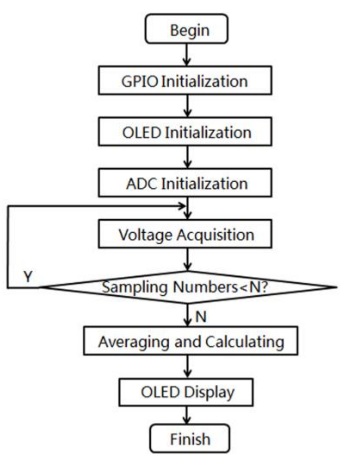

Fig. 5. Software design flow chart

Differential input mode was used for voltage acquisition to improve the test accuracy. At the same time, the extreme value filtering method was also adopted. By comparing data of N groups, the maximum value AD_VALUE_{max} and the minimum value AD_VALUE_{min} were removed. The average value of the remaining data is described as Eq.(4):

$$V = \left(\sum_{n=1}^{N-2} AD\_VALUE \right) \Big/ (N-2) \tag{4}$$

The corresponding relationship between AD sampling value and actual solar irradiation also needed to be determined. On account of 12-bit AD conversion module, the voltage resolution is calculated in Eq.(5) when the reference is 3.3V.

$$U_{\min} = \frac{3.3V}{2^{12}-1} = 0.806mV \tag{5}$$

The standard solar illumination *num* will be:

$$U_{\min} \le I_{sc} \times R = num \times EQE \times A \times e \times N_{ph0} \times R \tag{6}$$

The result is $num \geq 0.029$, it means that the test accuracy in theory can reach 0.029 standard solar illumination. In addition, the final result in this paper can be accurate to percentile.

Moreover, the reference voltage, sampling accuracy and conversion channel needed to be set. In this paper, the E1 channel in ADC1 module was adopted for data acquisition.

4. Results and discussion

4.1. Test result

In order to verify the performance of the test device, the monochromatic light was continuously adjusted and the equivalent standard solar irradiation was tested and calculated using standard solar cell chip. The curve was plotted according to the results. Table 1 shows the test and calculation results of solar illumination numbers.

Table 1. Solar illumination number test result

I_{sc}/A	standard solar illumination numbers/Suns
1.30	9.46
1.46	10.63
1.65	12.01
1.77	12.88
1.86	13.54
1.97	14.34
2.05	14.92
2.12	15.43

The corresponding curve can be seen in Fig. 6.

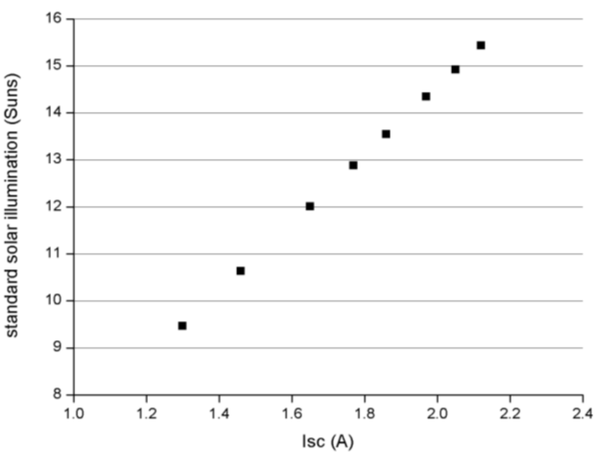

Fig. 6. The relationship between solar number and short-circuit current

As shown in the figure, the measured and calculated standard solar illumination had a good linear relationship with the short-circuit current, and this agrees with the relationship between light intensity and short-circuit current, indicating that the equivalent principle is correct. Meanwhile, from the test curve, the stability of this test device was proved. The data from the experiments confirmed that the monochromatic photon flux density could be precisely detected, then the standard solar illumination could be calculated, thus the purpose of testing the light intensity of the hydrogen platform has been achieved.

4.2. Experiments

The experiments of hydrogen passivation were conducted via the platform with high-intensity 940 nm LEDs as light source, as well as the intensity detector mentioned above. The size of 940 nm infrared LED array was 200 mm×200 mm. In the experiments, the light intensity (photon flux density) was adjusted to the irradiations of 15 standard suns, meanwhile, the silicon solar cell was heated at a temperature of 240℃, lasting for 1 minute. To analyze the effect of the experiment, LID of monocrystal Si PERC solar cells was carried out. In this process, the Xenon lamp was used to simulate the AM 1.5G solar spectrum. The light intensity of LID process was about 1KW/m^2 and the chamber temperature remained at 45℃. The LID irradiation processing lasted 5-hour. The electrical characteristics of the cells before and after the experiments are listed in Table 2.

Table 2. The electrical characteristics of the cells (monocrystal Si PERC cells, 156.75 mm×156.75 mm, ∅205 mm)

state	Voc(V)	Isc(A)	FF(%)	Efficiency(%)
Initial	0.6571	9.4837	79.41	20.380
After Hydrogen Passivation	0.6590	9.4978	79.76	20.556
After Light Induced Degradation	0.6571	9.4753	79.69	20.434

According to the references [16-18], to get a perfect hydrogenation effect, the light intensity needs to be over 10 suns. The result of the experiments showed that the electrical characteristics of solar cells were improved and the LID was abated after hydrogen passivation process and the effect was fairish. So it can be confirmed that the irradiation condition had met the requirement. Furthermore, the device we designed to measure and convert the monochromatic light photon flux density data to standard solar illumination is accurate.

5. Conclusion

The method to measure and convert the monochromatic light photon flux density to standard solar illumination to monitor the light intensity during hydrogenation process was developed. Moreover, a device to test the monochromatic light photon flux density was designed based on ARM Micro-controller, achieving the purpose of quick detection and display. The experiments confirmed that the high-intensity irradiation (photon flux density) of monochromatic light source could be accurately detected and displayed in real time, possessing a high practical value in the actual debugging and testing process.

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