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Comparative study of GaAs and CdTe solar cell performance under low-intensity light irradiance

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ABSTRACT

Comparative study of GaAs and CdTe solar cell under low-intensity light irradiance was carried out to study the cell device performance in response to the changed light irradiance intensity. For highly efficient GaAs solar cell, the series R_s and the shunt R_p resistance were found to be low/high enough to have almost undetectable negative effect on the cell device performance at low-intensity light irradiance. The robust diode parameters guaranteed good cell performance at low-intensity light irradiance. An ideal logarithmic function was established to describe the variation of cell efficiency with light irradiance intensity for GaAs solar cell. For CdTe polycrystalline solar cell, the relatively large series resistance R_s and small shunt resistance R_p, compared to that of the GaAs solar cell, significantly decreased the cell fill factor. With increased light illumination intensity, both the diode ideality factor A and the reverse saturation current density J_0 were increased due to the high density of interface states at the CdS/CdTe junction. The comparative study and conclusions drawn in this work provide device fabrication improvement direction for the CdTe solar cell.

1. Introduction

Both GaAs and CdTe have been proved to be efficient III-V and II-VI compound materials for solar cell fabrication. They have nearly ideal direct band gap structure with almost the same band gap values of 1.42 and 1.45 eV, respectively. The electronic band structures match well with the solar irradiation spectrum, leading to high photon absorption coefficient in the order of $10^4\,cm^{-1}$ for both materials (Myers et al., 1981; Moss, 1961; Casey et al., 1975). Thin film solar cells made of these two materials as absorber layer need a GaAs/CdTe film thickness of only one to several micrometers (Britt and Ferekides, 1993; Bosio et al., 2006; Bauhuis et al., 2009). This makes it possible to fabricate CdTe thin film solar cell with low material cost. Large-area CdTe solar module has been proved to be a competitive product in the photovoltaic market. GaAs solar cell is usually made of single crystal, while CdTe is made of polycrystalline thin film. The highest efficiency of GaAs and CdTe solar cell are 28.8 and 22.1% under the standard test condition (STC) of the AM 1.5 Sun spectrum with an intensity of 1000 W/m^2 (Green et al., 2016). GaAs solar cell modules are usually employed in situations where high solar to electric energy conversion efficiency is required, such as on a spacecraft or used as concentrated photovoltaics. Extensive study has been carried out on GaAs solar cell performance under high-intensity light irradiance (Algora et al., 2001; King et al., 2012). Recently we have studied the device performance of CdTe solar cell under high-intensity light irradiance (Li et al., 2014).

Solar cell module is employed under the natural sun light irradiation for electricity generation and most of the time it is working under lower light intensity than the standard test condition, which is the most intensive light irradiation that a solar cell can receive on the earth. Therefore cell device performance under low light irradiation is both scientifically and commercially important in regarding to the solar cell module fabrication. Until now seldom research has been carried out on the performance of both kinds of solar cells under weak light irradiance (Shen et al., 2016). In practice the natural outdoor sunlight irradiance usually has an intensity range of 100–1000 W/m^2. Detailed study of the cell performance under low light intensity helps us to understand physical processes and factors affecting device performance. For an ideal

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solar cell the illuminated current-voltage J-V curve is shifted straight upward from the dark J-V curve by a value of the photo-generated current density J_L. Different light illumination intensity not only changes the photo-generated current density J_L, but also has a great impact on the cell parameters, such as series resistance R_s, shunt resistance R_p, fill factor FF, diode ideality factor A and reverse saturation current density J_0. In this study, comparative study of GaAs and CdTe solar cell performance under low-intensity light irradiance was carried out. The two kinds of solar cells demonstrated relatively large device performance difference at low light-intensity irradiance. The variations of solar cell parameters with the irradiance light intensity were quantitatively analyzed. The experimental results demonstrated that highly efficient GaAs single crystalline solar cell has excellent device performance under weak light irradiance. An ideal logarithmic function was established to describe the variation of cell efficiency with light irradiance intensity. Through the analysis of this study we found that high efficient GaAs solar cell can act as device fabrication criterion for CdTe thin film solar cell.

2. Experimental

The GaAs solar cell in this study has a stacking structure shown in Fig. 1a. The layers with different kinds of doping were grown by using a molecular beam epitaxy (MBE) system, namely, Veeco GEN20A dual chamber (Veeco Instruments, Inc., Plainview, NY, USA), which is equipped with valved phosphorous and arsenic crack cells. The growth rate of GaAs and GaInP was 1000 nm/h. The n- and p-type GaAs were doped with silicon and zinc respectively at a growth temperature of 580 °C. In order to avoid indium desorption the GaInP layer was grown at a moderate low temperature of 470 °C. After MBE growth the structures were processed with the standard III-V solar cell device fabrication technique. AuGe/Ni/Au stacking structure was used as the front metal grid. Si_3N_4/SiO_2 was deposited on the device surface as the anti-reflecting coating layer. The GaAs cell size is $0.25 \times 0.25\ cm^2$.

The CdTe solar cell in this study has a structure of Glass/FTO/CdS/CdTe/Cu:Au/Ag back electrode, as shown in Fig. 1b. The CdS window layer, which was about 80 nm thick, was deposited on the FTO glass by chemical bath deposition (CBD) from a solution containing de-ionized water, cadmium acetate, ammonium acetate and thiourea. Heat treatment was then carried out on thin CdS film in a $CdCl_2$ atmosphere. The absorption CdTe layer with a thickness about 4 μm was deposited on the glass/FTO/CdS templates in a home-made close-spaced sublimation (CSS) system. The sublimation atmosphere was a mixture of O_2 and Ar with a certain pressure ratio. The sample was then subjected to a $CdCl_2$ activation heat treatment in the air atmosphere and etched in a nitric-phosphoric (NP) solution. Finally a Cu/Au bi-metal layer was grew by thermal evaporation as the back contact in a vacuum chamber. The CdTe cell size is $0.4 \times 0.4\ cm^2$. Detailed CdTe solar cell fabrication process is referred to our previous works (Yang et al., 2014).

The current-voltage J-V curves were measured by using a solar simulator (Oriel Sol 3A, USA), which has a standard AM1.5 (1 kW/m^2, 25 °C) illumination intensity. The weak light intensity less than the standard AM1.5 irradiance was obtained by employing neutral-density filters (Thorlabs NDK01, USA).

3. Results and discussions

3.1. The current-voltage curves of the GaAs and the CdTe solar cell

Fig. 2 shows the J-V curves of the GaAs and the CdTe solar cell measured under standard 1 Sun and different weak light irradiance intensity, respectively. The short-circuit current J_{sc} and the maximum power point current density J_{max} of both the two solar cells are linearly proportional to the light irradiance intensity as shown in Fig. 3. The variations of open-circuit voltage V_{oc} with the light intensity are shown in Fig. 4. The V_{oc} of both the solar cells are logarithmically increased with enhanced light intensity (Shen et al., 2016). The variations of the R_s and the R_p values of both solar cells with the light irradiance intensity are shown in Fig. 5. At the light intensity range from 1.0 down to 0.2 kW/m^2, both the series and the shunt resistance were increased only a little. However, when the light intensity was lower than ~0.2 kW/m^2, the R_s and the R_p resistance increased dramatically. For a semiconductor, when the irradiance light intensity is increased, the concentration of the photon-generated carriers is increased sharply, leading to much decreased electronic resistance. The electronic resistance R is related to the irradiance light intensity E, $R = \gamma \cdot E_{irra}^{-\chi}$, γ is a constant, χ is a parameter whose value depends on the specific material (Shen et al., 2016). The fittings, which are presented as the red[1] lines, are compared with the experimental data in Fig. 5.

The steady state light J-V characteristics of a solar cell based on one diode model is mathematically described by the following equation (Cuce et al., 2013; Lal and Singh, 2007; Khan et al., 2010; Agarwal et al., 1981),

$$J = J_L - J_0\left[\exp\left\{\frac{q(V+JR_S)}{Ak_BT}\right\} - 1\right] - \frac{V+JR_S}{R_p} \qquad (1)$$

where J_L and J are photocurrent and output current density, V is output voltage, J_0 and A are reverse saturation current density and ideality factor of the p-n junction, R_s and R_p are lumped series and shunt resistances of the equivalent circuit model for a solar cell. For the GaAs solar cell, the series resistance is mainly contributed by the film lateral resistance due to the lateral flow of the current in the emitter and window layers, and it is also contributed by the metal grid, which is made of 10 slim grid electrodes arranged in parallel on the $0.25 \times 0.25\ cm^2$ front surface (Algora and Díaz, 2000; Nishioka et al., 2006). For the CdTe polycrystalline solar cell, the series resistance is mainly contributed by the CdTe absorb layer due to the relatively low carrier concentration of $\sim 1 \times 10^{13}\ cm^{-3}$ and the Schottky barrier formed at the back contact (Li et al., 2014; Demtsu and Sites, 2006). Under STC, the R_s value of the GaAs solar cell is 2.1 Ω·cm^2, which is much smaller than that of 6.4 Ω·cm^2 of the CdTe solar cell, and the R_p value of 8986.2 Ω·cm^2 is significantly larger than that of 1017.9 Ω·cm^2 of the CdTe solar cell. The much smaller R_s and the significantly larger R_p of the GaAs solar cell indicate that the shape of the J-V curves measured under different light intensity would be much less influenced by the series and the shunt resistance compared to that of the CdTe solar cell.

In order to quantitatively demonstrate the influence of the R_s and the R_p on the shape of J-V curves, we assume the limit situation, namely, assuming $R_s = 0$ and $R_p = \infty$, and calculate J-V curves at different light irradiance intensity by using Eq. (1). In the calculations all the other parameters in Eq. (1) were taken from the experimental data. The model equations and the relevant parameters for the figure fittings in this study are listed in Table 1. Fig. 6 shows the comparison of the experimental J-V curves with the calculated ones for the two kinds of solar cells under STC and weak light irradiance. It can be seen that for the GaAs solar cell, the calculated J-V curves are in good agreement with the measured data. Under STC the calculated cell efficiency is 22.4%, the same as that of the measured one as shown in Fig. 6a. This suggests that the values of the series and the shunt resistance are low/high enough that they had negligible influence on solar cell performance for the GaAs solar cell at low-intensity light irradiance. For the CdTe solar

[1] For interpretation of color in Figs. 5 and 7, the reader is referred to the web version of this article.