Evaluation of electrical and optical characteristics of ZnO/CdS/CIS thin film solar cell

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In this study, device modeling and simulation are conducted to explain the effects of each layer thickness and temperature on the performance of ZnO/CdS/CIS thin film solar cells. Also, the thicknesses of the CIS and CdS absorber layers are considered in this work theoretically and experimentally. The calculations of solar cell performances are based on the solutions of the well-known three coupling equations: the continuity equation for holes and electrons and the Poisson equation. Our simulated results show that the efficiency increases by reducing the CdS thickness. Increasing the CIS thickness can increase the efficiency but it needs more materials. The efficiency is more than 19% for a CIS layer with a thickness of 2 μm. CIS nanoparticles are prepared via the polyol route and purified through centrifugation and precipitation processes. Then nanoparticles are dispersed to obtain stable inks that could be directly used for thin-film deposition via spin coating. We also obtain x-ray diffraction (XRD) peak intensities and absorption spectra for CIS experimentally. Finally, absorption spectra for the CdS window layer in several deposition times are investigated experimentally.

Keywords: CIGS solar cell, thin film, efficiency, CdS, XRD

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1. Introduction

CIGS-based thin film is one of the interesting absorbing materials for thin film solar cells,[1–3] owing to its suitable energy band-gap of the high optical absorption coefficient in the visible spectrum of sunlight. The absorption coefficient of CIGS film in the visible spectrum is, in fact, 100 times higher than that of the silicon film. Furthermore, the CIGS thin-film solar cell exhibits an excellent outdoor stability and radiation hardness and achieves the high conversion efficiency compared with other chalcopyrite and CdTe, and a-Si:H thin-film solar cells. The thin-film solar cell module based on CIGS is a technology for low-cost and large-scale photovoltaic applications. CIGS technology and material are highlighted because CIGS possesses low material consumption and relatively high efficiency and also has a tunable band gap, low radiation damage, and long-term stability.[1,4–6] CIGS solar cell is the representative of high efficiency solar cells with efficiencies around 20%.[4,7] Alternative buffer layers on CIGS solar cells can be used to enhance the lattice match between the absorber and the window; it improves the solar cell current generation and hence the efficiency. CdS has a good optical transmittance, a wide band-gap, and good electrical properties.[8,9] Increasing the CIS thickness can increase the efficiency but it needs more materials. The thin film solar cell is one of the research strategies for cost reduction.[10–12] The efficiency is more than 19% for a 2 μm-thick CIS layer. CdS thin film also has a high absorption coefficient, electron affinity, low resistivity, and easy Ohmic contact, also making it suitable for solar cell applications.[13] CdS is used as a window electrode because of its stability, reasonable conversion efficiency, and the deposition technique is low-cost. CIGS solar cells, which contain chemical-bath-deposited CdS, have attained a record efficiency of 20.3%. In this case, the CdS is the buffer layer. Another layer is the use of ZnO, because ZnO reduces the defect density of the surface and thus leads to reduced surface recombination. The calculations of solar cell performances are based on the solutions of the well-known three coupling equations: continuity equations for holes and electrons and the Poisson equation.[14,15] We use these equations to obtain open circuit voltage (V_{oc}), short circuit current density (J_{sc}), fill factor (FF), and efficiency (η) of a ZnO/CdS/CIS solar cell. Among all solar materials, the CIGS material is one of the best known light absorbing materials for thin film solar cells, owing to its direct band gap, tunable energy band gap, high optical absorption coefficient in a visible to near IR spectral range, acceptable energy gap, high stability when exposed to high energy incident light, and environment-friendly manufacturing process. In spite of this case, an efficient CIGS thin film solar cell has two main obstacles: first, an expensive vacuum based fabrication method such as two step sputtering deposition and multi-step co-evaporation. Second, it is difficult to control stoichiometry on large and industrial scales. Therefore, it is important to use a non-vacuum method to fabricate the CIGS thin films.[4,16–20]

In the present paper we use simulation and experimental results to show the influence of layer thickness and also the effect of temperature on the performance of CIS based solar cell. Since the optical properties of the CIS layer can be controlled

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during deposition,[5,21–24] the influences of CIS thickness and its absorption are also investigated experimentally. The solar cell efficiency and spectral response dependences on thickness and temperature are simulated to determine the limiting factor of the cell performance. The merit of numerical simulation is to predict the results and the influence of the process parameters on the device without implementing fabrication. However, we obtain some experimental results like the effects of CIS and CdS thickness on absorption.

2. Results and discussion

A CIGS solar cell is typically composed of several layers having a thickness of about 2 μm. Reducing such a thickness without degrading their performance is more important. It helps solar cell industries to cut down the deposition time of the CIGS thin-film and reduce the production cost by saving the raw materials. There are some drawbacks caused by the reduction of the absorber layer thickness, reported in detail in Refs. [25]–[27]. In this section we simulate CIGS cells that are schematically shown in Fig. 1(a). The simulations are carried out at several different thickness values of layers when changing the absorber thickness value. We investigate the effect of the absorber layer thickness on the electrical output characteristics of the solar cell. The energy band diagrams of simulated solar cells are shown in Fig. 1(b). The charge carrier generation takes place in the absorber material as a result of solar radiation. The generated electrons move to the conduction band. Because of the band bending, the electrons are transported to the front contact. The holes in the valence band are transported to the back contact. To enable an effective charge transport in the conduction and valence band, the different barriers ($\Delta E_{\rm VB}$ and $\Delta E_{\rm CB}$) at the interfaces between the materials must be as low as possible.

The CdS layer and CIS in the structure constitute a heterojunction. The thickness of CdS should be as thin as possible. Also, the high band gap of the CdS is useful for high optical throughput with minimal resistive loss. For this reason, the CdS layer is commonly considered as a window layer in the CIS solar cell. In the following we calculate several important parameters which are used to characterize solar cell performances. The short-circuit current ($J_{\rm SC}$), the open-circuit voltage ($V_{\rm OC}$), the fill factor (FF), and the efficiency are all parameters determined from the I–V curve. Figure 2 shows the

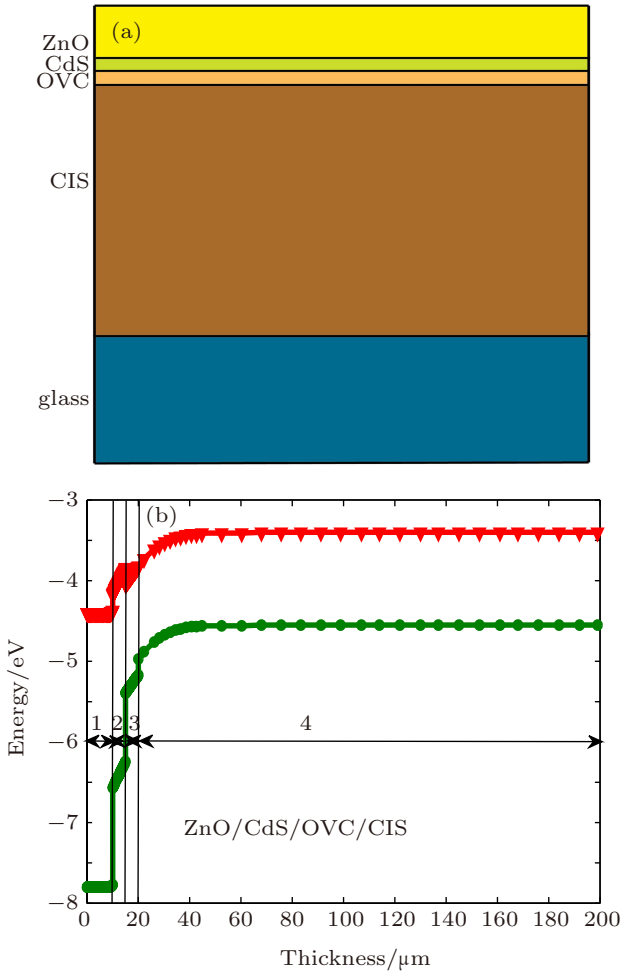


Fig. 1. (color online) (a) Schematic diagram of simulated device, and (b) band diagram of the ZnO/CdS/OVC/CIS solar cell.

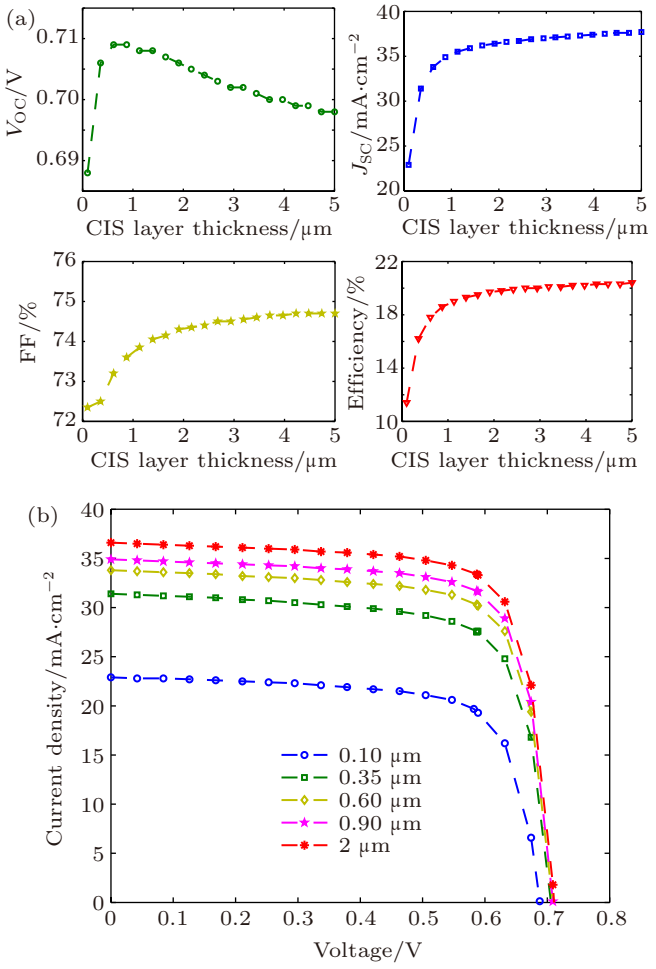


Fig. 2. (color online) (a) Performance parameters of simulated cell each as a function of CIS thickness, and (b) current–voltage characteristics of CIS solar cells with CIS thickness values of 0.1 μm, 0.35 μm, 0.6 μm, 0.9 μm, and 2 μm.

variations of the CIS solar cell parameters as a function of CIS layer thickness. The thickness of the CdS is fixed at 10 nm. Figure 2(a) displays the short-circuit current (J_{SC}), the open-circuit voltage (V_{OC}), the fill factor (FF), and the efficiency of a simulated cell as a function of CIS thickness, respectively in its panels. The efficiency increases with increasing the absorber layer thickness. Figure 2(b) shows current voltage characteristics at CIS thickness values of 0.1 μm, 0.35 μm, 0.6 μm, 0.9 μm, and 2 μm. J_{SC} and V_{OC} are valuable parameters at the I–V curve of solar cell.

Then we find the dependence of output parameters on CdS thickness. In this section the thickness of the CIS is fixed at 2 μm. we calculate the current–voltage characteristics and spectral responses each as a function of CdS window layer thickness. Figure 3(a) shows I–V curves for CdS thickness values of 10 nm, 20 nm, 30 nm, 40 nm, and 50 nm. Figure 3(b) shows spectral responses of the mentioned solar cells with CdS thickness values of 20 nm, 50 nm, and 200 nm. As a result the performance of the cell is degraded with increasing the CdS window layer thickness. The spectral response is drastically degraded when the CdS thickness exceeds to 200 nm. An increase of the CdS layer increases the light absorption in this layer to the detriment of the CIS absorber layer, thereafter the cell efficiency is degraded. The optical band gap of the window layer is larger than that of the CIS, an increase in the window layer changes the absorption in the shorter wavelength range of visible spectrum as seen in Fig. 3(b), showing the variation of the solar cell spectral responses with CdS thickness.

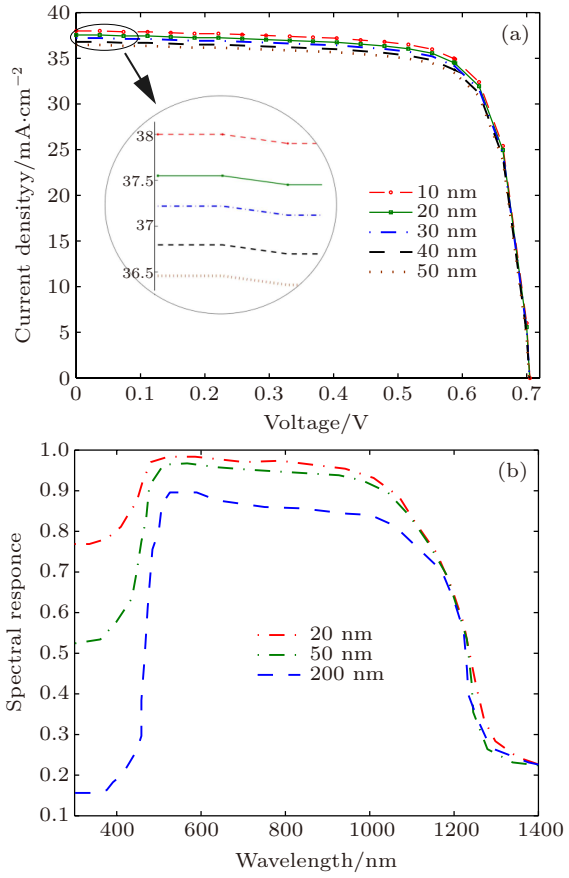


Fig. 3. (color online) (a) I–V curve of the CIS solar cell each as a function of CdS thickness, and (b) calculated quantum efficiencies of CIS solar cells with CdS thickness values of 20 nm, 50 nm, and 200 nm.

We investigate the effects of thickness of both window and absorber layers. In the above we have reported the variations of the solar cell efficiency with CdS and CIS thickness respectively. We have considered the case where front layer thickness is 50 nm and the absorber layer thickness is 2 μm. Now we achieve the output cell parameters as a function of ZnO thickness. Figures 4(a)–4(d) show the variations of short-circuit current (I_{SC}), open-circuit voltage (V_{OC}), fill factor (FF), and efficiency verses ZnO thickness with ZnO thickness.

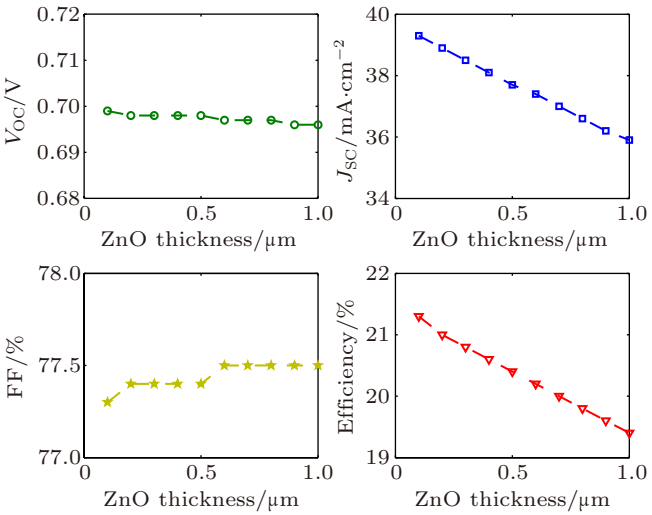


Fig. 4. (color online) Output parameters of simulated solar cell varying with ZnO thickness.

The characterization of solar cell is usually performed at a temperature of 300 K and an irradiation of one sun concentration. However, in many applications, the actual operating conditions differ strongly from these laboratory conditions. In this section, we simulate temperature-dependent output parameters of CIGS solar cell at temperatures ranging from 300 K to 500 K in steps of 50 K. Temperature-dependent output parameters are extracted.

Figure 5(a) shows the temperature dependent current–voltage characteristics of a CIGS solar cell. As temperature increases, for all component cells the band gap decreases, leading to the reduction in open circuit voltage. In Fig. 5(b) we summarize the short-circuit current (I_{SC}), the open-circuit voltage (V_{OC}), the fill factor (FF), and the efficiency each as a function of temperature. The increase of temperature will degrade the cell performances. It is clear that efficiency decrease is mostly due to open circuit decrease with temperature increase.

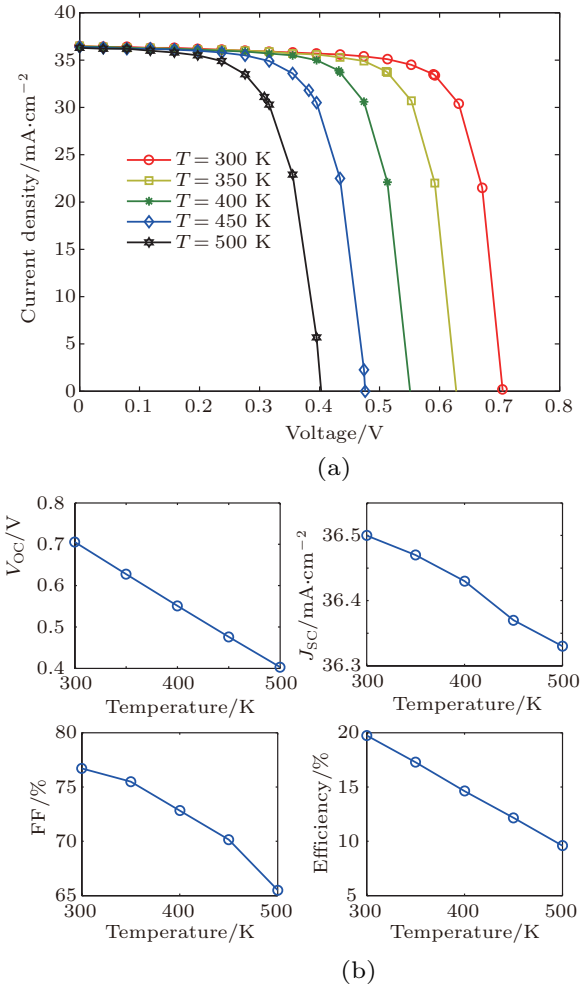


Fig. 5. (color online) (a) *I*–*V* curves of the simulated solar cell at temperatures of 300, 350, 400, 450, and 500 K, and (b) cell performance parameters varying with temperature.

3. Experimental results

Crystal structure and absorption spectrum of CIGS nanoparticles and the morphology of the thin film are studied by XRD, UV-visible spectrometer and high resolution scanning electron microscopy (HRSEM) in an acceleration voltage of 20 keV, respectively. For optical characterization, CIGS nanoparticles diffuse in chloroform at room temperature, and then turned into an ink. The ink is deposited by dropping on a soda lime glass substrate in constant time intervals, while the substrate spins with a speed of 1500 r/min. Then, it is placed on a hot plate with a temperature of 150 °C for 1 min in order to evaporate the solvents. Spin coating processes are repeated to reach the desired thickness. Its spectrum is measured in a wavelength range of 600 nm–1100 nm. The structural and optical properties of the resulting CIS QDs are investigated using composition analysis, absorption spectroscopy. Highpurity CIS is synthesized by using this process. It is examined by using an x-ray diffraction (XRD) pattern, and figure 6(a) shows the XRD pattern of synthesized CIS. The diffraction peaks of (112), (220)/(204), (312)/(116), (400), and (316) planes

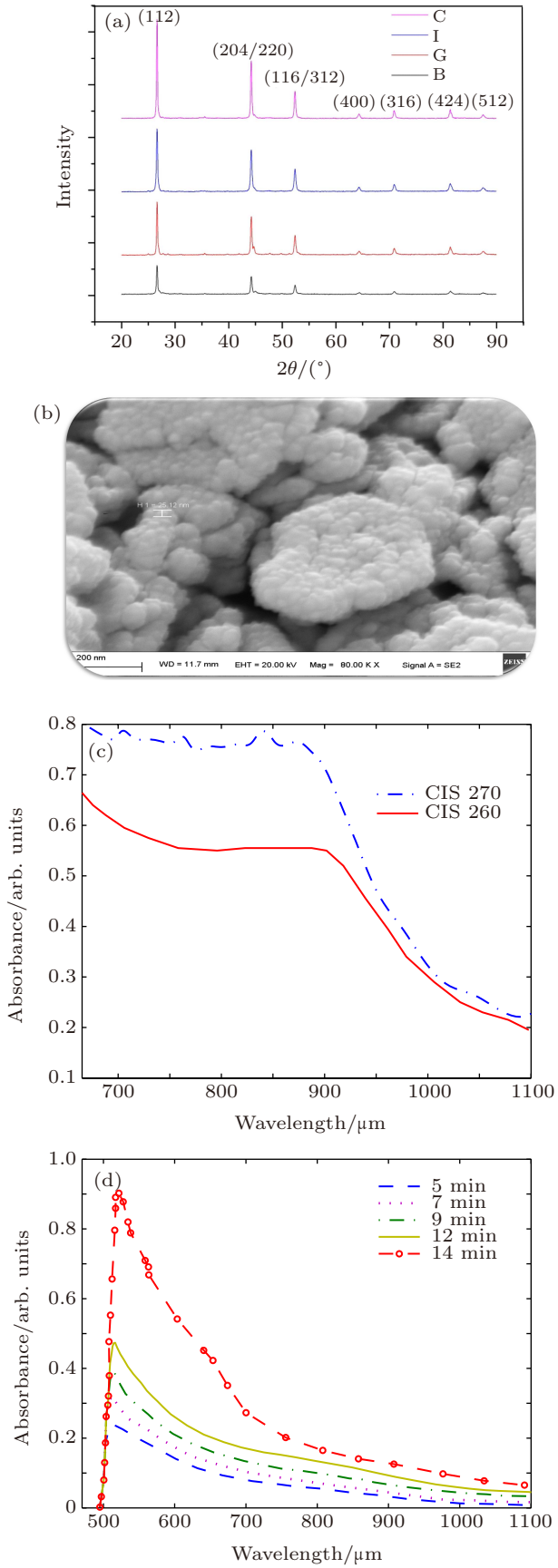


Fig. 6. (color online) (a) X-ray patterns of the synthesized CIS at temperatures of 260, 270, 280, and 290 K with a reaction time of 1.5 h, (b) micrograph of the synthesized CIS, (c) absorption spectra of CIS QDs synthesized under temperatures of 260 K and 270 K and reaction time of 1.5 h, and (d) absorption spectra of CdS varying with wavelength for different reaction times.

are found. The XRD pattern proves that the suitable phase is formed in the hydrothermally synthesized CIS, and no secondary phase is observed. A micrograph of the synthesized CIS is shown in Fig. 6(b). Finally, absorption spectra of CIS QDs synthesized under various temperatures and reaction times are measured. Absorption spectra for a reaction time of 1.5 h with temperatures of 260 K and 270 K are shown in Figs. 6(c). As shown in the figure, the absorption at a higher temperature has a higher value. Also the absorption spectra of CdS as a function of reaction time are depicted in Fig. 6(d). The thicker CdS layer absorbs light of wavelength near 0.5 μm as expected but the generated carriers do not contribute to the output current. So, a lower reaction time for CdS deposition is suggested.

4. Conclusions

In this paper, we simulate the effects of the thickness and temperature on the performance of ZnO/CdS/CIS solar cell. The obtained results indicate that the reduction in CdS window layer thickness enhances the solar cell efficiency. The cell efficiency is more sensitive to the absorber layer thickness; the increase in CIS thickness will enhance the efficiency. Also, we conclude that ZnO thickness can affect the cell output parameters. Finally, the influence of temperature on the cell performance is calculated. It is also found that the XRD peak intensities and absorption spectra of CIS quantum dots are obtained experimentally at different synthesis temperatures. This seems to suggest that CIS cores synthesized at higher temperatures could provide a better absorption. Also absorption spectra of CdS as a function of reaction time are obtained experimentally. A thicker CdS layer absorbs the light with wavelength near 0.5 μm but the generated carriers do not contribute to the output current. So, a lower reaction time for CdS deposition is suggested.

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