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The influence of incident angle on physical properties of a novel back contact prepared by oblique angle deposition

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ABSTRACT

In this paper, oblique vacuum thermal evaporation and direct current (DC) magnetron sputtering technique are used to produce a novel back contact electrode (BCE) of $CuInS_2$ solar cell. These novel back contact electrodes (BCEs) are based on a layered structure of Mo/Ag/Mo (MAM). The influence of vapor source incidence angle θ on optical-electrical properties of novel BCE is investigated by X-ray Diffraction (XRD), Surface Profiler, Atomic Force Microscope (AFM), UV-vis-IR Spectrometer, and Four-point Probe Method. According to the analysis of AFM images of BCEs, the variation tendencies of surface roughness and uniformity are closely related to the incidence angle θ. The surface roughness increases with the increase of incidence angle θ, but the uniformity becomes poor at same time. This phenomenon can be attributed to the variation of interlayer Ag films (the density and inclined angle of Ag nanorods). The results of four-point probe test show that the novel BCE deposited by vapor source incidence angle θ equal to 45° owns the lowest resistance value of 3.71×10^{-8} Ω m, which is probably due to a loose and multi-point contact interface between Ag layer and top layer (Mo_2). The reflectance of novel BCEs deposited by incident angle less than 45° is higher than that of normal bi-layer Mo (Mo_{12}) BCE. As a result, the efficiency of corresponding solar cell may be upgraded.

1. Introduction

$CuInS_2$ (CIS) is a promising ternary compound semiconductor for solar cell absorber layer. CIS has a high optical absorption coefficient of $10^5 cm^{-1}$, absorbing solar radiation up to 90% with the thickness of 1–2 μm [1,2]. The back contact electrodes (BCEs) play an important role in hetero-junction CIS-based solar cell with a multi-layer structure of BCE/CIS/CdS/ZnO, which must have following performances [3], (1) form ohmic contact with absorber layer; (2) chemical inertness and stability; (3) good adhesion and uniformity; (4) High reflectance; (5) low resistivity; (6) resistance to form alloy with Cu and In elements. In this paper, it focuses on the study of resistivity and reflectance of the BCEs. A variety of BCE metals, such as W, Cr, Mo, Ta, V, Ti, Mn, et al, have been investigated [4]. Among them, Mo is the most widely used BCE metal due to its remarkable advantages. In addition, a thin interlayer MoS_2 can be used to form good ohmic contact with CIS absorb layer. The performances of BCE have significant impact on the nucleation, growth and morphology of absorber layer, and the further effect on the efficiency of the solar cells. Conventionally, a Mo bi-layer film, used as BCE, is successively deposited by sputtering method [5]. In the previous study [6], the change of resistivity and adhesion of Mo BCE as a function of sputtering gas pressure has been studied. The results show that Mo film deposited by high gas pressures has good adhesion but bad resistivity, whereas Mo film deposited by low gas pressures shows opposite performances.

Oblique angle deposition (OAD) basically combines a typical physical deposition system with a tilted and rotating substrate [7]. The oblique angle incidence flux enhances atomic shadow effect and produces an inclined columnar microstructure under the limited adatom diffusion [8]. The density and the height of inclined nanorods are influenced by the incident angle θ. The OAD method has been used in many applications, such as optical anisotropy films [9], wideband circular polarization reflector [10] et al. Surface roughness in aluminum thin film using OAD method has been studied [11]. The surface roughness is highly related to incident angle θ, which may have an influence on the resistivity and reflectance of the BCEs.

It is well known that the optical-electrical properties of the film are strongly associated with the thickness and morphology, which are depended on the incident angle θ. It was reported that the

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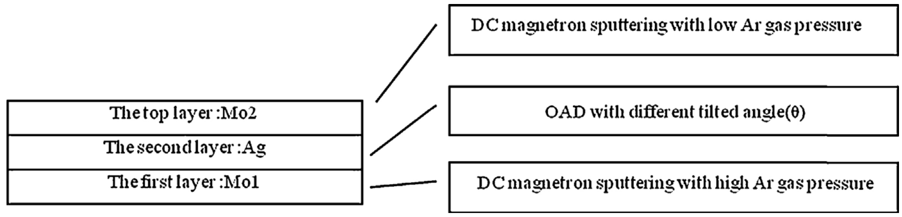

Fig. 1. The structure of novel BCE.

incident angle 45° is a critical angle to decide the morphology of the film prepared by OAD method. So, in this paper, the author selected three angles (5°, 45°, 60°) for the deposition of Ag to study the influence of incident angle on the properties of the BCE. A novel BCE based on a layered structure is prepared by following process steps, as shown in Fig. 1. The first layer (Mo_1) is sputtered with high Ar gas pressure to obtain good adhesion with the substrate. The second layer (Ag) is deposited by OAD technique to obtain low resistance and rough surface. The top layer (Mo_2) sputtered by low Ar gas pressure has lower resistance than that of Mo_1 layer, which also has good adhesion with CIS absorbed layer. The influence of vapor source incidence angle θ on the optical-electrical properties of novel BCEs is investigated by XRD, Surface Profiler, AFM, UV-vis-IR Spectrometer, and Four-point Probe Method.

2. Experiment procedure

The Mo_1 thin film was sputtered by DC magnetron sputtering with Mo target (99.99%, Φ = 60 mm) on 3 cm × 2 cm SLG substrate, which was cleaned by de-ionized water, acetone and alcohol in ultrasonic cleaner and then dried by N_2 flux. The deposition chamber was evacuated by a turbomolecular pump to a base pressure of 6.5×10^{-4} Pa and the Ar-partial pressure of 1.5 Pa was electronically controlled by a valve. The substrate-to-target distance was 15 cm and the sputtering power was 60W. Then the Ag film was deposited by oblique vacuum thermal evaporation at a base pressure of 10^{-3} Pa on the surface of Mo_1 thin film. During the deposition of Ag film, the substrates were tilted with a certain angle in the range of 5–60°. The deposition angle is defined to be the angle between the incident flux and the axis perpendicular to the substrate surface. All the substrates with different oblique angle were mounted on the sample holder, which were 20 cm away from the source. The deposition time was 5 minutes. After the deposition of Ag layer, Mo_2 thin film was sputtered by DC magnetron sputtering system on the condition of sputtering power of 80W and Ar-partial pressure of 0.5 Pa. Moreover, reference samples, Mo_1, Mo_2 and Ag thin film, were obtained at each process step during the growth of BCEs. The novel BCEs with different deposited angles are named as MAM5°, MAM45° and MAM60°, respectively.

A four-point probe method was used to measure sheet resistances (R_s) of BCEs and reference samples, and the thicknesses (h) of BCEs and reference samples were measured by Alpha Step 500 surface profiler. The XRD analysis using a Rigaku D/MAX-III X-ray diffractometer with graphite monochromatozed CuK_α radiation (λ = 0.1541678 nm) was used to determine the structure and the preferred growth orientation of BCEs and reference samples. The UV–vis–IR spectra were measured by UH4150 spectrometer with scan speed 300 nm/min and slit width quantitative 4 nm in the range of 200–1000 nm. The AFM, conducted by Scanning Probe Microscope SPM-9600 system with a triangular microstructure cantilever, was used to study the morphology and the surface roughness of BCEs. All of the measurements were carried out at room temperature under ambient atmosphere.

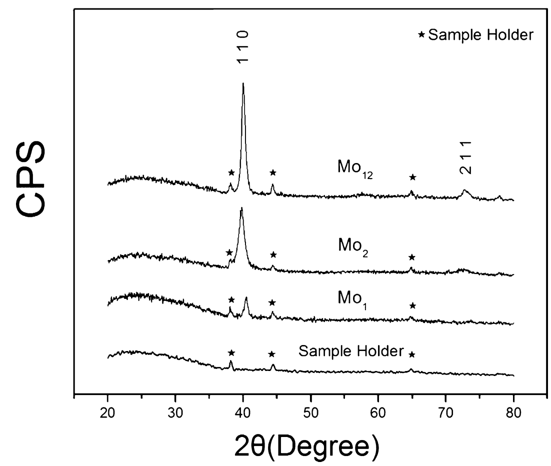

Fig. 2. XRD pattern of Mo_1, Mo_2 and Mo_{12} thin films.

3. Results and discussion

Fig. 2 displays the XRD spectra of Mo_1, Mo_2 and Mo_{12} thin films. Comparing with JCPDS card (42-1120), the diffraction peaks of (1 1 0) and (2 1 1), respectively centered at $2\theta \approx 40.46°$ and $2\theta \approx 73.75°$, are obviously observed for Mo phase with typical face-centered cubic structure. As shown in the XRD patterns, Mo_1, Mo_2 and Mo_{12} thin films exhibit a preferred growth orientation along (110) plane. It is strange that the unconspicuous peaks centered at $2\theta \approx 37.5°$, $2\theta \approx 45.5°$ and $2\theta \approx 65.5°$ are not any phase of the BCE, which might be related to the ones of the sample holder. Comparing with the XRD curves of Mo_1 and Mo_2 thin films, the smaller full width at half maximum (FWHM) of diffraction peaks of Mo_{12} thin film indicates good crystal quality.

The inter-planar spacing d is calculated by Bragg equation ($\lambda = 2d \sin\theta$), where λ is X-ray wavelength and θ is diffraction angle. With diffraction peak of (1 1 0) plane, the lattice parameter a is calculated by planes-spacing formula of face-centered cubic structure: $d_{hkl} = a(h^2 + k^2 + l^2)^{-2}$. The grain size D of Mo_1, Mo_2 or Mo_{12} thin film is calculated by scherrer formula: $D = 0.9\lambda/(\beta \cos\theta)$, where β is FWHM of (1 1 0) plane. All the calculated structure parameters of Mo_1, Mo_2 and Mo_{12} thin films are presented in Table 1. The lattice parameter a of Mo_2 (low Ar gas pressure) is 3.1973 Å, which is larger than that in JCPDS card (42-1120, 3.1462 Å). In addition, inter-planar spacing $d_{(110)}$ of Mo_2 is also larger than that in JCPDS card, indicating the existence of high compressive stress [12,13]. In contrast, the inter-planar spacing $d_{(110)}$ and the lattice parameter

Table 1
Structure parameters of Mo_1, Mo_2 and Mo_{12} thin films.

Sample	$d_{(110)}$ (Å)	a (Å)	D (Å)	FWHM (°)
Mo_1	2.2234	3.1444	165	0.5221
Mo_2	2.2608	3.1973	116	0.7322
Mo_{12}	2.2500	3.1820	149	0.5761