Characterization of photoconductive CdS thin films prepared on glass substrates for photoconductive-sensor applications

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Cadmium sulfide (CdS) thin films with n-type semiconductor characteristics were prepared at room temperature on glass substrates by radio-frequency magnetron sputtering for photoconductive-sensor applications. Films deposited at room temperature exhibit polycrystalline phases and show smooth surface morphologies. The deposition rate of the films decreases with increasing working pressure. The dark- and photoresistances in 400-nm-thick CdS films deposited at $6.7 \times 10^{-1}$ Pa and 80 W were approximately $1 \times 10^5$ and $3 \times 10^4$ Ω/sq, respectively. Lowering both the dark- and photoresistances lowers the sensitivity ($R_{dark}/R_{photo}$) of the resistance. © 2008 American Vacuum Society. [DOI: 10.1116/1.2945301]

I. INTRODUCTION

Cadmium sulfide (CdS) thin films have received growing interest over the past three decades due to their electro-optical properties, which are suitable for applications in the field of optoelectronic devices, particularly solar cells, and photodetectors. CdS is a nonstoichiometric n-type semiconductor with a direct band gap energy of 2.42 eV (bulk CdS). In order to allow most of the optically excited electrons to pass through the film, the densities of trapping and recombination centers have to be relatively low. A low resistivity and a high photosensitivity are required for photoconductive-sensor applications. The band gap of CdS is in the range of visible light and the photosensitivity in the visible range is very high for CdS films.

CdS films have been prepared by several methods, such as chemical-bath deposition, electrochemical deposition, pulsed-laser deposition, and rf magnetron sputtering. Since nonvacuum techniques of film deposition are inherently more susceptible to contamination, only vacuum-deposition techniques have been studied for CdS film preparation.

In this study, CdS films were prepared at room temperature on glass substrates by rf magnetron sputtering. Their structural and photoconductive properties were mainly investigated with variations in working pressure. These properties were also studied for the effects of rf power and film thickness.

II. EXPERIMENTAL PROCEDURE

CdS films were deposited on glass substrates (Corning 1737) at room temperature by the rf magnetron sputtering technique using Ar gas with a CdS target (hexagonal structure with purity of 99.99%) of 2 in. diameter. The substrate was rotated on its axis at 24 rpm for homogeneous deposition of the films. The base pressure for the deposition was approximately $2.7 \times 10^{-4}$ Pa and the working pressure was varied from $2.7 \times 10^{-1}$ to $27 \times 10^{-1}$ Pa. The rf power for film deposition also was varied from 20 to 120 W. The distance between the target and the substrate is approximately 12 cm. The morphologies and film thickness were investigated through the surface and cross-sectional images, respectively, using scanning-electron microscopy (SEM) (Topcon DS-130C). The root mean square (rms) roughness of the films was measured using atomic-force microscopy. The charge-carrier density and the mobility of the films were investigated by Hall measurement (HMS 3000). The sheet resistance ($R$) of the samples was measured by an electrometer (CMT-SR 1000) using a four-point probe. The schematic diagram for the measurement of sheet resistance is shown in Fig. 1. First, CdS films were deposited at room temperature on glass substrates. Subsequently, 100-nm-thick Ag electrodes of $10 \times 10$ mm² were deposited on CdS films by dcmagnetron sputtering. The gap between Ag electrodes was approximately 5 mm. The sheet resistance of samples was measured at room temperature using a digital multimeter (HP3458A). The photoconductivity of the films was measured in air ambient after the sample was light soaked for 15 min by white light from a 100 W quartz lamp.
III. RESULTS AND DISCUSSION

Figure 2 shows the variations in deposition rate of CdS films deposited on glass substrates at room temperature and at rf power of 50 W as a function of working pressure. As shown in Fig. 2, the deposition rate of the films decreases monotonously with increasing working pressure. In this experimental condition, a decrease in deposition rate with increasing working pressure was attributed to the scattering effect of the particles detached from the target by argon plasma. An available thickness of CdS films can be chosen from these data in terms of variations in working pressure. In order to investigate whether the films have a crystalline structure, x-ray diffraction (XRD) patterns of the films deposited at various working pressures are shown in Fig. 3a. As shown in Fig. 3a, films deposited at various working pressures exhibit a polycrystalline nature having (002) and (101) planes and the peak intensities of (002) plane increase with increasing working pressure. XRD patterns of the films strongly support that the CdS films deposited at room temperature are crystallized at various working pressures. The variations in grain size of the films as a function of working pressure are shown in Fig. 3b. The grain sizes in CdS films can be calculated using the full width at half maximum of (002) peaks in Fig. 3a using Scherrer’s formula. The grain size of the films shows the maximum of about 32 nm at 6.7×10⁻¹ Pa and then decreases with increasing working pressure above 6.7×10⁻¹ Pa. The inset in Fig. 3b shows SEM surface images of the films deposited at 2.7×10⁻¹ and 6.7×10⁻¹ Pa.

![Fig. 1. Schematic diagram for the measurement of sheet resistance.](image1)

![Fig. 2. Variations in deposition rate of the CdS films deposited on glass substrates at room temperature as a function of working pressure.](image2)

![Fig. 3. (a) X-ray diffraction patterns of the films deposited at various working pressures and (b) the relationship between the grain size and working pressure. The inset in (b) shows SEM surface images of CdS films deposited at 2.7×10⁻¹ and 6.7×10⁻¹ Pa.](image3)
The surface images show dense and homogeneous morphologies, although the working pressure increases. The rms roughness of the films linearly varies from 1.2 to 3.5 nm with increasing working pressure from $2.7 \times 10^{-1}$ to $27 \times 10^{-1}$ Pa (not shown here).

Figure 4 shows the variations in dark- and photoresistance as a function of working pressure. The film thickness for measurement of sheet resistance was maintained at 400 nm, irrespective of working pressure. As shown in Fig. 4, the dark- and photoresistances vary with a consistent trend for variations in working pressure and show the lowest values in the films deposited at $6.7 \times 10^{-1}$ Pa, followed by an increase in sheet resistances with increasing working pressure above $6.7 \times 10^{-1}$ Pa. The resistivity of the semiconductor materials depends on the product of charge-carrier density and the carrier mobility. In RuO$_2$ films, the carrier mobility is inversely proportional to the film roughness and the carrier concentration is proportional to the grain size.\textsuperscript{13} The conduction of CdS films at room temperature can also be explained considering the microstructural aspects. From the results of grain size [see Fig. 3(b)] and rms roughness, the sheet resistances of the CdS films with working pressure strongly depend on the variations in charge-carrier density rather than the mobility. A Hall effect in films deposited at $6.7 \times 10^{-1}$ Pa shows an electron-charge density of $9.87 \times 10^{16}$/cm$^3$ and a carrier mobility of 6.6 cm$^2$/V s. A decrease in both dark- and photoresistances produce a decrease in the difference between dark- and photoresistance. The dark- and photoresistances in CdS films deposited at $6.7 \times 10^{-1}$ Pa were approximately $1 \times 10^5$ and $3 \times 10^4$ $\Omega$/sq, respectively.

Figure 5 shows the variations in dark- and photoresistance of the films deposited as a function of radio-frequency power in a working pressure of $2.7 \times 10^{-1}$ Pa. For variations in rf power, dark- and photoresistances vary in the ranges of $10^6$ and $10^5$ $\Omega$/sq, respectively. The inset in Fig. 5 shows the variations in sensitivity of sheet resistance as a function of rf power. The sensitivity is defined as $R_{\text{dark}}/R_{\text{photo}}$ and the higher sensitivity is required in a low sheet-resistance region for photoconductive-sensor applications. From the inset, films deposited at 50 W show the highest sensitivity of the sheet resistance.

Figure 6 shows the variations in dark- and photoresistances as a function of film thickness. The films were deposited at working pressure of $2.7 \times 10^{-1}$ Pa and rf power of 80 W. The sheet resistances of the films decrease with increasing film thickness, as shown in Fig. 6. As shown in an inset of Fig. 6, the films of 300 nm thickness show the highest sensitivity and then the sensitivity slightly decreases with increasing film thickness above 300 nm. The result is that the lower the dark- and photoresistances, the lower the photosen-
sitivity of the resistance. In the case of the films with lower dark resistance, adequate charge carriers already exist in the conduction band in the dark state, and illumination by the light source is less effective in the production of charge carriers for photoconduction.

IV. CONCLUSIONS
Cadmium sulfide thin films were deposited at room temperature on glass substrates by rf magnetron sputtering for photoconductive-sensor applications. The CdS films deposited at room temperature for various working pressures exhibit polycrystalline phases and show dense and smooth surface morphologies. The dark- and photoresistances in CdS films deposited at $6.7 \times 10^{-1}$ Pa were approximately $1 \times 10^5$ and $3 \times 10^4$ Ω/sq, respectively. In the films deposited at various parameters, lowering both the dark- and photoresistances lowers the sensitivity of the resistance.

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