Vacuum 84 (2010) 119–122

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

Application of wide angle beam spectroscopic ellipsometry for quality control in solar cell production

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Keywords:
Spectroscopic ellipsometry
Wide angle beam ellipsometry
Transparent conductive oxide (TCO)

ABSTRACT

Wide angle beam ellipsometry developed by our group uses non-collimated illumination with a special light source and arrangement giving multiple-angle-of-incidence and multiwavelength information. Our aim was to make our wide angle beam ellipsometer suitable for spectral measurement and to obtain the spectra of many points along a long line (presently 0.2 m but it could be increased up to 1 m if necessary) of an entire sample simultaneously. The prototype uses a xenon lamp as a light source with film polarizers and a concave optical grating to reach the desired 6 nm spectral resolution over the range of 360–630 nm. This new technique mixed with an appropriate ellipsometric model has the capability to make "*in situ*" control in solar cell fabrication. In order to demonstrate the ability of our instrument, wide angle beam spectroscopic ellipsometry measurements were carried out on Al-doped ZnO samples, which have different physical properties such as specific resistance and transparency.

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1. Introduction

Ellipsometry is an important non-destructive measurement technique for process or quality control in solar cell production. Usually, spectroscopic ellipsometry measurements are carried out with a millimetre sized beam however if the lateral distribution of optical properties of a sample surface is of interest, measurements can be carried out point by point by mechanical scanning. This is usually not a practical solution to obtain the spectra of many points because it takes much time.

For this purpose, imaging spectroscopic ellipsometry methods have been developed. The scanning methods, based on the conventional single-narrow-beam measurements are very accurate but make these methods relatively slow for mapping purposes. The wide angle beam imaging techniques based on a detector matrix can speed up the measurement. In these cases the surface is illuminated by a non-collimated light beam and the reflected light is detected mostly by a CCD camera [1–4]. In this way, many points of the surface are measured simultaneously and the measured values are evaluated as an image to determine the lateral distribution. A disadvantage of the method is that measurements can only be carried out at one wavelength simultaneously.

Our aim was to develop a new instrument (based on wide angle beam ellipsometry) which has the capability to obtain 50 spectral points (over the range of 360–630 nm) with better than 10 mm lateral resolution of many sample points simultaneously. Demonstrative measurements were carried out on different Al-doped ZnO samples. The measurement evaluations show that spectroscopic ellipsometry combined with the wide angle beam method offers a non-destructive in-line characterization tool for the deposition process.

2. Experimental

To reach our purpose a redesign of the optics of our wide angle beam ellipsometer [4] was necessary. Fig. 1 shows the side view of the optical arrangement.

In this promising approach a rectangular (narrow) aperture is (Fig. 1) placed in the light path close to the fibre end that provides a thin, long illuminated line on the sample (5) surface from end to end. After reflection from the sample the beam propagates up to a cylindrical mirror (6). A Cylindrical mirror is placed in the light path for correction of the aberration (mostly astigmatism) caused by the tilted spherical mirror. The corrected beam comes through the analyzer (8) and a pinhole (9), and reaches the corrector-disperser optics. (11) This contains a cylindrical, spherical lens pair and a concave optical grating. The dispersed beam is detected by a ccd camera (12). In the given configuration a lateral resolution of

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doi:10.1016/j.vacuum.2009.05.013

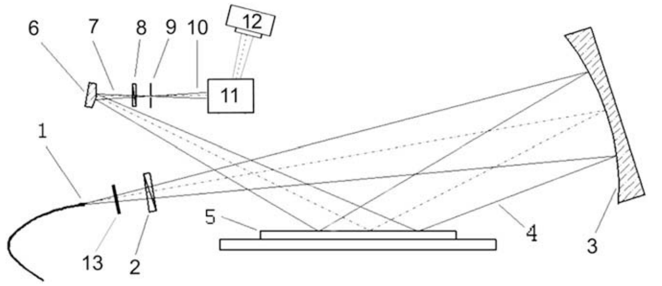

Fig. 1. Side view of the optical arrangement. (1) point source; (2) polarizer; (3) spherical mirror; (4) non-collimated beam; (5) sample; (6) cylindrical mirror; (7) corrected beam; (8) analyzer; (9) pinhole; (10) beam after pinhole; (11) corrector–disperser optics; (12) ccd detector; (13) rectangular (narrow) aperture.

8 mm and 50 spectral points of each lateral point is detectable simultaneously.

Geometrical image analysis was carried out to estimate the spectral resolution of the given optical arrangement. The expected spectral resolution is better than 6 nm over the used spectral range (360–630 nm). It provides 50 measured spectral points in the visible range from a 200 mm long and 4 mm wide sample surface in only one measuring cycle. The length of the measured line could be scaled up arbitrarily. The necessary angle-of-incidence and the optical element-effect calibration are made via well-known and optimized structures such as silicon/silicon-dioxide samples [3]. A xenon lamp (which provides many discrete lines in the applied spectral range) was used to make wavelength calibration, which is essential to evaluate the measurements.

The Al-doped ZnO layers were deposited by DC reactive magnetron sputtering [5]. The target was a high purity Zn 99.95%, alloyed with 2% Al. ZnO depositions were made onto two 4 inch silicon substrates placed side by side (see Fig. 8) in an Ar/O_2 atmosphere, revealing lateral inhomogeneity in the deposition chamber. Other experimental details are given in Ref. [5].

Resistance measurements were carried out with the well-known 4-probe method. Specific resistances were calculated using the thickness values from the ellipsometric measurements.

3. Results and discussion

Since our layers are of dielectric character, i.e. of minor absorption in case of higher conductivity transparent layers, and the band-gap equivalent wavelength λ_0 lies outside our spectral range, a good and robust choice for the fitting is the Cauchy dispersion relation:

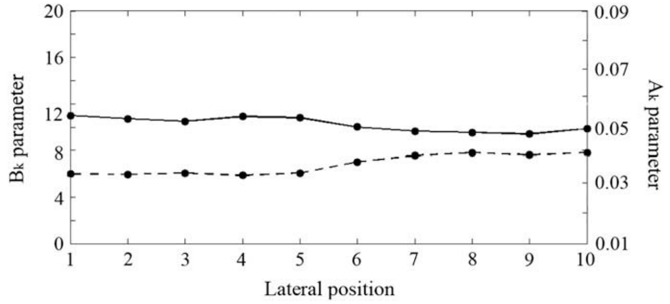

Fig. 3. A_k (dashed line) and B_k (solid line) parameter as function of position of sample D14B.

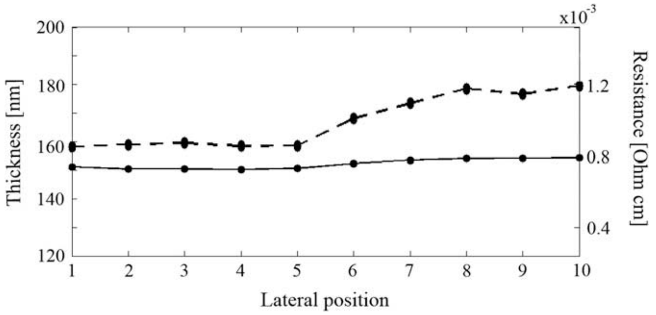

Fig. 4. Resistance (dashed line) and thickness (solid line) as function of position of sample D14B.

$(\lambda) = A_n + B_n/\lambda^2 + C_n/\lambda^4$, $k(\lambda) = A_k \cdot \exp(B_k \cdot (1/\lambda - 1/\lambda_0))$ where $\lambda_0 = 360$ nm is the wavelength corresponding to the band-gap value.

A 3-phase model (ambient, ZnO layer, substrate) was used to evaluate the measurements in this analysis. The results show that the samples (which have different electrical and optical behaviour) have different model parameters, thus the samples can be characterized by spectroscopic ellipsometry measurements. Six parameters were fitted (five of the dispersion relation plus one layer thickness) using the least squares method, in order to minimize the difference between the measured and fitted ellipsometric curves. As reported in ref. [5], the amplitude (A_k) and the exponent (B_k) of the imaginary part of the complex refractive index function depend on the transparency and correlate with the specific resistance of the layers. The following screening criteria are observed: $A_k < 0.03$ for the required transparency condition (higher than 80–85% over the range of 400–800 nm) and $B_k > 0.3$ for the required resistance

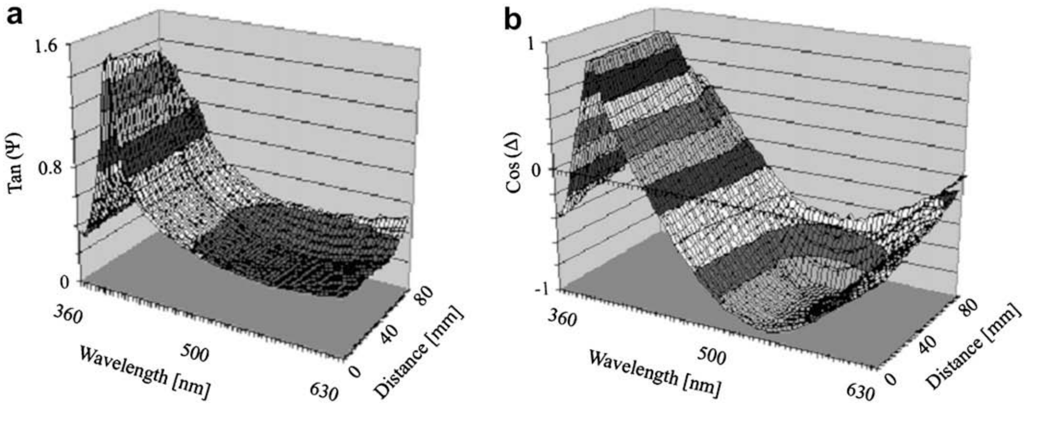

Fig. 2. Measured tan(Ψ) (a) and cos(Δ) (b) of sample D14B.

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