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Measurement of the zinc oxide–molybdenum specific contact resistance for applications in Cu(In,Ga)Se_2-technology

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ABSTRACT

We developed an improved measuring structure based on the transmission line model (TLM) which allows us to determine the specific contact resistance between rf-sputtered aluminum doped zinc oxide (ZnO:Al) and dc-sputtered molybdenum despite inhomogeneities in film thickness and conductivity which normally prevent an accurate determination of this value with the TLM. The improvement was achieved by an interchange between the contact and the conduction bar material to get a lower resistance of the conduction bar. Using this structure, the specific contact resistance is ascertained to be $(1.37 \pm 0.14) \times 10^{-5}\ \Omega\ \mathrm{cm}^2$. In addition, the effects of variations of certain sputter deposition parameters and their influence on the specific contact resistance are demonstrated. In particular, a small amount of oxygen in the sputter gas during the molybdenum sputter process remarkably increases the specific contact resistance.

1. Introduction

For an optimization of the integrated series connection of Cu(In,Ga)Se_2 (CIGS) thin-film solar cells, it is important to know the exact specific contact resistance between aluminum doped zinc oxide (ZnO:Al) and molybdenum (Mo). This knowledge allows the calculation of the exact series resistance of CIGS solar cell modules with tens to hundreds of such contacts and to search for an optimum between the contact widths, the current transport and the loss of active area as discussed e.g. by Burgelman et al. [1]. In opto-electronics, many efforts have been made to determine the specific contact resistance between ZnO:Al and different metals [2,3]. Unfortunately, the literature values for the specific contact resistance between ZnO:Al and molybdenum vary in the range from $2 \times 10^{-4}\ \Omega\ \mathrm{cm}^2$ to $0.2\ \Omega\ \mathrm{cm}^2$ [4–6]. This large uncertainty of the parameter prevents exact calculations of optimized cell interconnections. Furthermore, the wide spread of the data may indicate a certain dependence of the specific contact resistance on the deposition methods and the parameters used. Therefore, the influence of the parameters of the rf- and dc-sputtering processes on the specific contact resistance should also be elucidated. We perform I-U-measurements at specially designed test structures the results of which are analysed by means of the transmission line model (TLM) [7]. Since the contact distances of our samples range from 1.5 to 25 mm, no complex techniques such as lithography are needed to pattern the sample structure and conventional shadow masks were used instead. But, together with the relatively large contact distances, the typical test structure, which is shown in Fig. 1a, led to a large inaccuracy of the values determined for the specific contact resistance due to inhomogeneities in the ZnO:Al-layer which are not taken into account in the theory. The problem was solved by designing an optimized test structure for such large distances, in which the contact and the conduction bar material are interchanged. This allows us to get more precise results for the specific contact resistance between ZnO:Al and molybdenum which will be presented in this paper. In addition, the sputter deposition parameters of the layers of the structure were varied and their influence on the contact resistance was monitored.

2. Theory

As H.H. Berger showed [7], in the case of direct current, the resistance R_C between a semiconductor and a metal can be calculated by

$$R_C = \frac{\sqrt{R_S \cdot \rho_C}}{w} \times coth\left(\frac{d}{L_T}\right), \tag{1}$$

where R_S is the sheet resistance of the semiconductor bar, ρ_C is the specific contact resistance, d is the length and w is the width of the contact and L_T is the transfer length given by

$$L_T = \sqrt{\rho_C / R_S}\ . \tag{2}$$

The typical structure is shown in Fig. 1a with the important dimensions given in Fig. 1c. Plotting the resistance between two contacts

$$R(l) = 2R_C + \frac{R_S}{w} \times l \tag{3}$$

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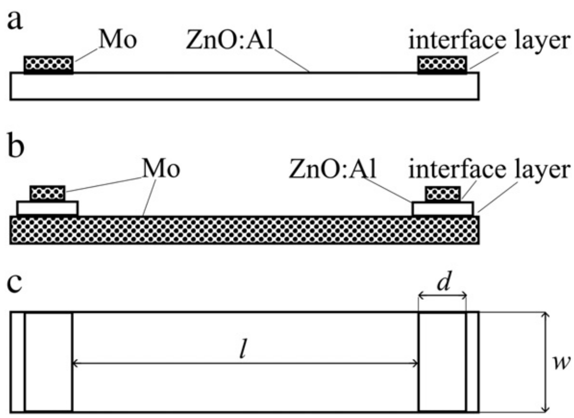

Fig. 1. a) Conventional TLM test structure for determination of Mo-ZnO:Al-specific contact resistance (cross section), b) improved TLM test structure (cross section), and c) geometric dimensions of the TLM test structure (top view).

versus the distance l of the contacts yields $2\times R_C$ by extrapolating to $l=0$ and R_S by multiplying the slope of the graph with w. However, if the TLM is used for analysis and if a certain lateral inhomogeneity is present in the sheet resistance of the semiconductor layer, the determination of the contact resistance will be inaccurate because the TLM does not take inhomogeneities into account. This inaccuracy increases with both the absolute value of the sheet resistance and its variation. In the present case, this effect made the conventional determination of the contact resistance impossible due to a variation of the ZnO:Al-layer thickness caused by the specific sputter process. Hence, a kind of inverted TLM structure was designed in order to overcome this problem. Fig. 1b shows the modified structure. The resistivity of molybdenum is about three orders of magnitude lower than that of ZnO:Al and so inhomogeneities in the sheet resistance of the molybdenum lead to much smaller errors. Moreover, the intersection of the $R(l)$ plot with the y-axis at $l=0$ is now four times R_C instead of two times R_C because there are four ZnO:Al–molybdenum interfaces in the structure. Furthermore, using Eq. (1) to analyse the data measured with the inverted structure, only a vertical current flow is allowed through the ZnO:Al contact pads. Assuming an isotropic specific conductivity of the ZnO:Al-layer, the lateral resistance in the whole ZnO:Al-contact pad is about six orders of magnitude higher than the vertical resistance due to the geometric dimensions. Thus, the assumption that there is no lateral current in the ZnO:Al contact layer is a very good approximation. Moreover, this vertical resistance should be negligible when compared to the contact resistance. This was proven experimentally as discussed in the first paragraph of Section 4.

3. Experimental details

The deposition of the test structure is carried out in two separate sputter chambers. The molybdenum is sputtered with a dc-magnetron source and the ZnO:Al with a rf-magnetron source. Each layer of the structure is sputtered with a separate shadow mask made of stainless steel. The conduction bar has a width w of 1.2 mm. The molybdenum contact pads have the same width and a length d of 0.5 mm (see Fig. 1c for an explanation of the geometric dimensions). The dimensions of the ZnO:Al contact pads are a little bit larger than those of the molybdenum pads as it is drawn in Fig. 1b in order to prevent leakage currents. However, with the approximation that there is only a vertical current flowing through the ZnO:Al, only the dimensions of the molybdenum contact pad are essential. The substrate is a 10×10 cm^2 soda lime glass. The glass is washed in a mixture of deionized water and pure tenside and subsequently dried under flowing nitrogen gas. Directly before sputtering the molybdenum conduction bar, the glass is additionally cleaned by plasma etching in an atmosphere of argon plus two percent oxygen. The bar itself is composed of two layers of molybdenum following the idea of Scofield et al. [8]. Here, the first layer provides the adhesion between the molybdenum and the glass whereas the second layer provides a high conductivity. These properties of the molybdenum layer are realised by changing the sputter pressure between the deposition of the first and second layer. The first layer with a thickness of about 200 nm is sputtered at 250 W in pure argon (5 N) at a pressure of 2.0×10^{-2} mbar. The pressure during the sputter process of the second layer was varied between 2.0×10^{-3} and 8.0×10^{-3} mbar as an experimental parameter just as the gas was varied between pure argon and argon with two percent oxygen. The sputter power for the second molybdenum layer was always 800 W. The molybdenum contact pads were always sputtered under the same conditions as the second layer of the molybdenum conduction bar to get the same interface. ZnO with an amount of two weight percent Al_2O_3 was sputtered at 200 W and 2.0×10^{-3} mbar in pure argon. Here, only the thickness of the ZnO:Al layer was varied between 120 and 480 nm. Using a third structure, the sheet resistance of the ZnO:Al-layer was measured to calculate its specific resistance. This structure consists of several parallel ZnO:Al-bars with a width w of 1 cm and a total length of 10 cm. The thickness is an experimental parameter. Onto these bars equidistant molybdenum contacts are sputtered. The width w of the contacts is equal to the ZnO:Al-bar (1 cm), the length d is 0.5 cm, and the distance between two adjacent contacts is also 1 cm. Using this structure, we can directly measure the sheet resistance of a sample with a spatial resolution of around 1 cm^2. The last experimental parameter comprises the possibility of a plasma etching step before sputtering the ZnO:Al and the molybdenum contact pads. The etching step takes 90 s at a direct current of 100 mA.

4. Results and discussion

Fig. 2 shows the variation of the ZnO:Al specific resistance with changing film thickness. A decrease of the specific resistance with increasing layer thickness is observed, which is also described in the literature [9,10]. Because the resistivity is about four times higher at 120 nm (extrapolated from the data of Fig. 2) than at 480 nm, the vertical resistance remains nearly constant over the whole range and was calculated to be about 4×10^{-6} Ω. The lowest values of $R(l=0)$ extrapolated from our measurements are about 0.04 Ω. Thus, the vertical resistance of the ZnO:Al contact pad is more than three orders of magnitude smaller than R_C and is thus negligible, as it is assumed in the theory. Another demonstration of the independence of the specific contact resistance and the ZnO:Al-layer thickness is shown in Fig. 3. The calculated specific contact resistance is plotted versus the

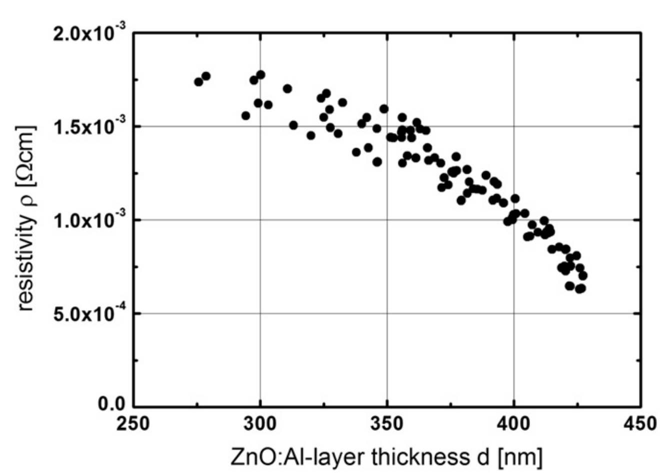

Fig. 2. Dependence of the specific resistance of the ZnO:Al-layer on the ZnO:Al-layer thickness.