Large area Sputtered ZNO Films as Substrates for Highly Efficient Silicon Thin-Film Solar Modules

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Solar cells based on hydrogenated amorphous (a-Si:H) or microcrystalline (µc-Si:H) silicon offer a number of advantages as compared to the widely used mono- or multi-crystalline silicon technology. Low material consumption due to the small film thickness, low process temperatures, only moderate energy demand and the use of low-cost substrate materials (floatglass, metal- or plastic-foils) make them an ideal candidate to achieve a substantial cost-reduction in large area solar modules. Transparent conductive oxide (TCO) used as front contact material plays a crucial role in obtaining high efficiencies with a-Si-H and µc-Si:H based solar cells. Besides combining a low series resistance with high transparency, it also has to provide an adequate surface texture for optimized light scattering. Moreover, the TCO is an important cost factor for module production.

In recent years, aluminum-doped zinc oxide (ZnO:Al) films prepared by rf- or dc-magnetron sputtering have emerged as a material with the potential to fulfill all of the above requirements. Initial efficiencies up to 9 % for µc-Si:H single junction and 12.5 % for a-Si/µc-Si tandem junction cells on rf-sputtered ZnO-substrates have already been achieved on laboratory-scale. To further push this development towards an industrial mass production, the up-scaling of ZnO-sputtering and ZnO-adapted solar cell processes from laboratory size to large areas (0.6 m^2) is currently being performed

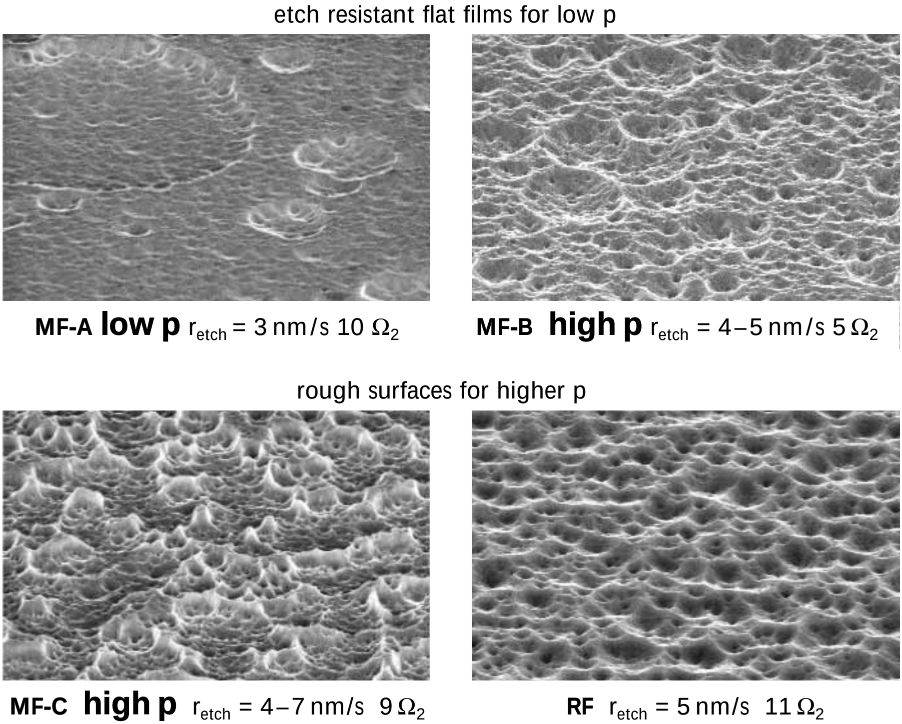

Figure 1
SEM images of wet-chemically etched ZnO films prepared by reactive mf-sputtering at different sputter pressures. For comparison, a state-of-the-art rf-sputtered film is included.

within a joint R&D project between industry and research institutions. One of the main innovations of the project is the use of the mid-frequency (mf) reactive sputter technique based on dual cathodes in a TwinMag™ arrangement. This process yields highly conductive and transparent films. Furthermore, it can significantly reduce TCO costs by using cheaper metallic Zn:Al targets and by allowing very high sputter rates. The required surface texture of the ZnO is achieved by a simple wet-chemical etching process.

This paper reports the current status of the project. High dynamic sputter rates of 700 – 1000 nm•mm/s were already achieved, corresponding to static rates of approximately

200 – 300 nm/min. All films were highly transparent and had specific resistances of 3 - $9 \cdot 10^{-4}$ Ωcm (best value: $2.6 \cdot 10^{-4}$ Ωcm). In general, preparation at low sputter pressures leads to etch-resistant films, which develop only a slight surface roughness with insufficient light scattering properties upon etching in 0.5 % HCl. Higher sputter pressures, on the other hand, yield rough, textured surfaces after the etching step making them suited for the application in solar cells *(see Fig. 1)*.

Before applying them as front contacts in amorphous silicon (a-Si:H) p-i-n solar cells the etched films were subject to an evaluation procedure describing the total losses in large area modules due to TCO sheet resistance and absorbance. In such an analysis the mf-sputtered ZnO films are amongst the best candidates for the use in module production *(Fig. 2)*.

Having proven the excellent suitability of texture-etched ZnO, a further optimization of the process is expected to lead to large area ZnO films produced by cost-effective reactive mid-frequency sputtering for the next generation of highly efficient thin-film silicon solar modules.

Figure 2
Total electrical and optical losses in a-Si/a-Si tandem solar modules due to TCO sheet resistance and absorbance for various types of TCO films. Note that light scattering is not included in the evaluation procedure.