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Degradation of flexible thin-film solar cells due to a mechanical strain

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ABSTRACT

Many variants of thin film technology are nowadays part of the photovoltaic market. The most popular are amorphous silicon, CIS (Copper Indium Selenide)/CIGS (Copper Indium Gallium Selenide)/CIGSS (Copper Indium Gallium Sulphur Selenide), and CdS/CdTe (Cadmium Sulphide/Cadmium-Telluride) cells. All mentioned types allow potentially for a flexible cell structure. Most emitter contacts are currently based on TCOs (Transparent Conductive Oxides), however, wider approach with alternative carbon nanoforms, silver nanolayers and polymer materials, called TCLs (Transparent Conductive Layers) are also in use. Authors decided to investigate influence of mechanical stresses on physical and electrical behaviour of these layers. Consequently, the aim of work is to determine the level and possible mechanisms of flexible a-Si cell parameters degradation due to a deterioration of transparent contact properties.

1. Introduction

1.1. Flexible solar structures

One of the most popular thin film structures–amorphous silicon cells are manufactured in lower temperatures than standard silicon devices, usually not exceeding 200 °C. A typical production technology of α-Si solar cells is based on a PECVD (Plasma Enhanced Chemical Vapour Deposition) process in which SiH_4 silane is decomposed to create thin amorphous layers on different substrates [1]. Solar cells produced by this method have a high absorption rate of the base material reaching even $10^6\,cm^{-1}$ for a light wavelength below 400 nm and they may have thickness of an absorber layer reduced ten times in comparison to typical polycrystalline cells. This technology may be used to produce monolithic cells in both substrate and superstrate configuration. Thanks to the mentioned issues, it is currently evaluated as one of the promising candidates for flexible, mobile applications. It should be noted that in both elastic and rigid structures employing amorphous silicon as emitter contacts, layers of the conductive oxides–TCOs are used [2].

Similarly, thin-film cells based on semiconductor compounds may be nominated to the role of flexible, wearable solar structures. For example, CIS/CIGS/CIGSS cells which are placed amongst popular TF (Thin Film) structures. Currently, at least 34 companies worldwide are working on starting production or improving already produced CIS/CIGS/CIGSS modules employing various laboratory techniques for that purpose [3]. Also cadmium telluride based solar cells are one of the most promising devices in thin film photovoltaics. Low-cost soda-lime glass, foil or polymer film can be used as the substrate of a CdTe/CdS solar cell. The best results of 21% efficiency [4] are achieved with glass substrate. However, Laboratory for Thin Films and Photovoltaics at EMPA (Swiss Federal Laboratories for Materials Science and Technology), obtained 12.7% efficiency of a single CdTe solar cell on a polymer foil and 7.5% of a monolithically interconnected flexible CdTe solar module of a 32 cm^2 total area [5]. For efficient functioning, these structures need durable flexible transparent emitter contacts as well.

2. Degradation of various TCOs' parameters in bending tests

Since most of the popular transparent emitter contacts currently manufactured in industrial flexible cells are based on TCO materials, a set of these layers was identified for degradation measurements. Normalized A-De Mattia PN-EN ISO7854 test (Fig. 1) procedures were performed for testing of their electrical parameters degradation due to a static and dynamic bending.

During the experiments, cylinders with a diameter within the range of 25 mm ÷ 75 mm were used. According to the norm conditions each time the length of a sample allowed for the 180° angle bending of the tested material. For the initial verification of resistivity degradation three popular metal oxides applied in thin-film solar cells construction were tested. In this case a ZnO:Al layer deposited on a PET (Polyethylene terephthalate) foil using a PLD (Pulse Laser Deposition) method and ITO (Indium Tin Oxide) by magnetron sputtering as well as TiO_2 layers were examined. On-

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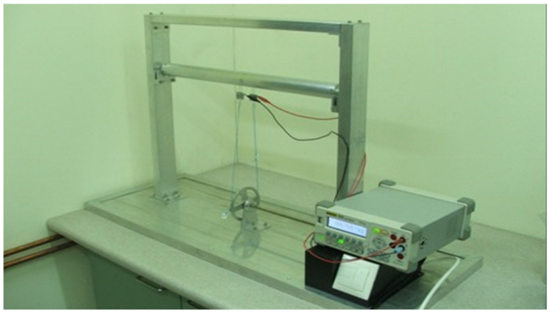

Fig. 1. Laboratory set-up, used in the experiments for dynamic bending tests according to the A-De Mattia method.

line results were collected by a digital Rigol multimeter. Obtained results for various oxides (Figs. 2 and 3) gave the comprehensive insight into the mechanisms and the level of TCO layer degradation in mobile, flexible applications.

As a result of bending to a full angle on a 25 mm diameter cylinder, the structure was almost completely destroyed. This resulted in a catastrophic resistance per square rise of over 6000% for an ITO contact after just about 200 bending cycles. For all TCO layers the main reasoning of this phenomenon was the micro-cracks' development. A detailed surface analysis of critical bends and cracks of the contact structure with widths from 0.1 μm up to even 8 μm and an average interval of about 50 μm is presented in Fig. 4.

3. Influence of TCO contacts deterioration on final cell parameters

The most interesting analysis concerning the TCO damage during bending is the influence of this process on the final cell degradation and particular mechanisms causing a subsequent efficiency drop. For this study the measurements of real flexible cells, contacted by an ITO layer, as well as numerical simulations were undertaken. The commercial flexible α-Si Power Film MP-37 mini-module with the maximum peak power of 150 mW was used for bending experiments. The initial I–V characteristics, as well as basic parameters, are shown in Fig. 5.

The tested cell of the total thickness of 220 μm was selected owing to specific properties and construction details. An examined mini-module is composed from an a-Si structure, based on a flexible metal foil and encapsulated by a standard PET which enables high pliability. Front contacts are constructed by an ITO layer connected

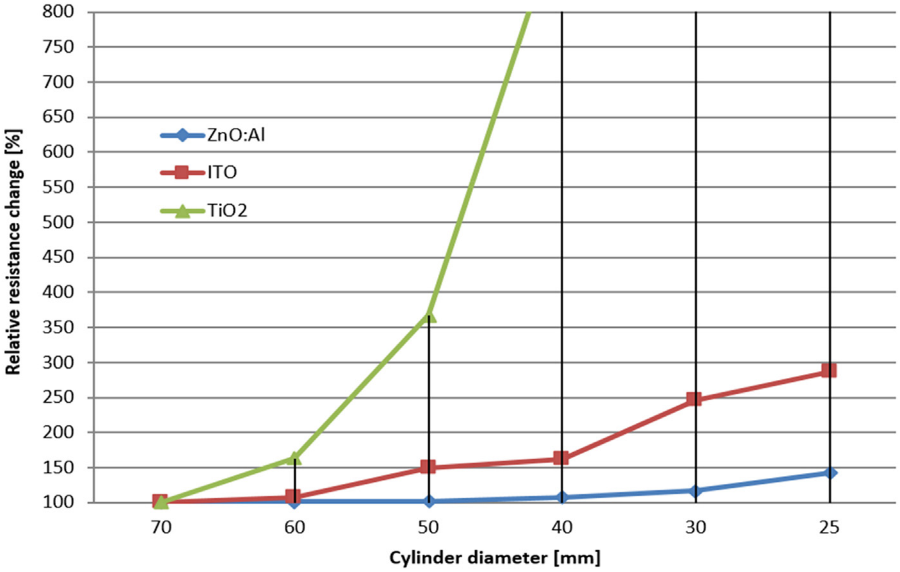

Fig. 2. Relative resistance change of typical TCOs, deposited on a PET foil in static bending tests on various cylinders.

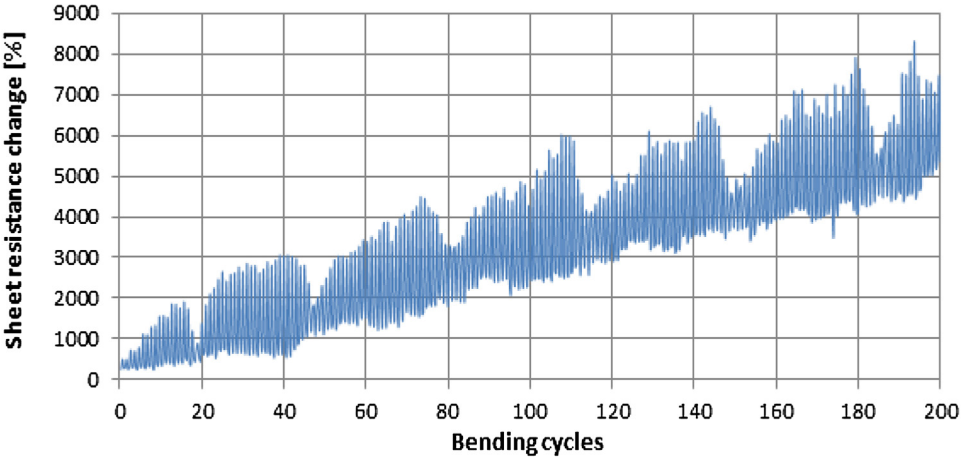

Fig. 3. Sheet resistance (per square) growth of a 150 nm ITO layer on a PET foil in a dynamic bending test on Ø = 25 mm diameter cylinder.

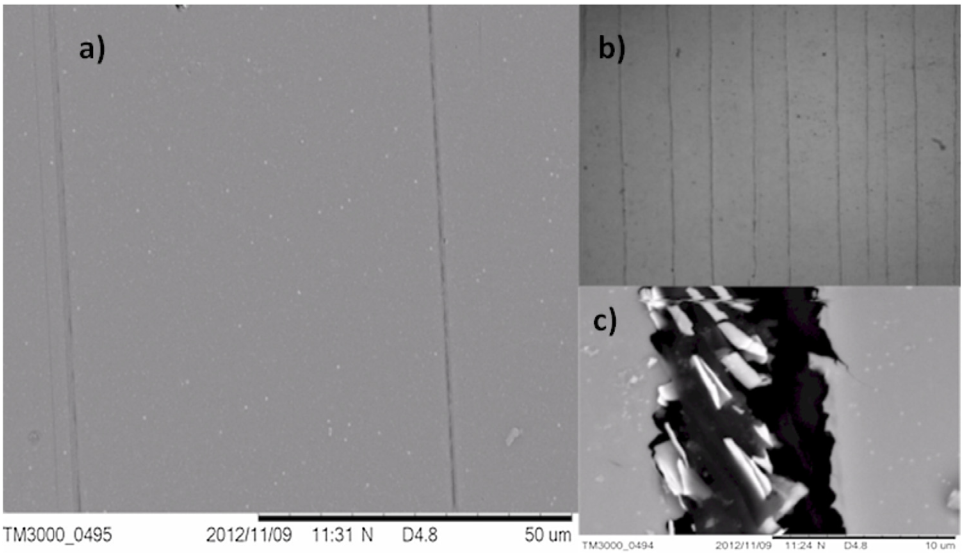

Fig. 4. SEM image of standard micro cracks of the ITO layer on PET which resulted from bending to a full angle on a Ø = 25 mm diameter cylinder (a), a series of micro crack visible in an optical microscope–magnified × 100 (b) and a critical massive crack on a SEM picture (c).

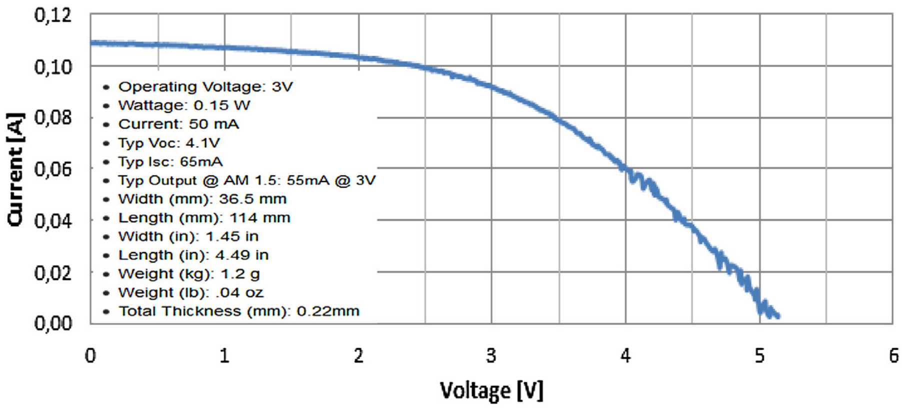

Fig. 5. Measurements of I–V characteristics and basic parameters of a MP-37 mini–module.

Table 1
MP-37–electrical parameters degradation in a dynamic bending test.

Number of bends	Isc [mA]	Voc [V]	P_{MAX} [mW]	η [%]
0	109.04	5.14	279.84	9.89
7500	99.55	4.69	169.56	5.97
15 000	78.89	4.62	147.96	5.23
22 500	65.46	4.62	113.41	4.01

to metal bars. The complete module properties were verified in static and long-term dynamic bending test. All electric parameters were measured and compared with reference results for PET/ITO samples. Summarized results are presented in Table 1.

4. Modelling of ITO degradation influence on flexible cell internal parameters

Comprehensive measurements of a bent MP-37 cell structure I–V characteristics allowed for modelling of internal parameters deterioration. Fig. 6 shows the current-voltage and power characteristics of cells measured during bending tests.

By using of the Sol-Cell-Tracer program package, the VDEM (One Variable Double Exponential Model) model of the bent structure was adjusted for each measurement cycle. By adjusting of the proper weight function the accordance higher than 98% for each characteristics was achieved. By adjusting of these parameters, authors achieved a proper simulation model for an in-deep analysis of the cell degradation mechanisms. On the basis of each calculation all specific parameters, including R_s and R_{sh} were extracted for each tested sample. Exemplary results of this process are given in Fig. 7.

5. Conclusions

After series of experiments some conclusions on the final cell performance, as well as the degradation structure process may be drawn. Bending tests of various TCOs on PET foils proved that inorganic transparent contacts based on metal oxides are highly ineffective in flexible applications. Rapid growth of sheet resistance for each of these layers, with the value as high as 7000% after only two hundred of bends, was spotted. In this case the most popular ITO is also vulnerable to mechanical stress. Application of a TCO layer thickness sufficient for satisfying value of initial sheet resistance leads inevitably to micro-cracks in bending tests.

Measurements of commercial flexible modules contacted by ITO also confirmed significant, however not so drastic parameters' degradation. The efficiency drop to the 50% of initial value was not observed before 15,000 bends at a 25 mm cylinder. Even though the TCO structural damage was detected, no significant increase of

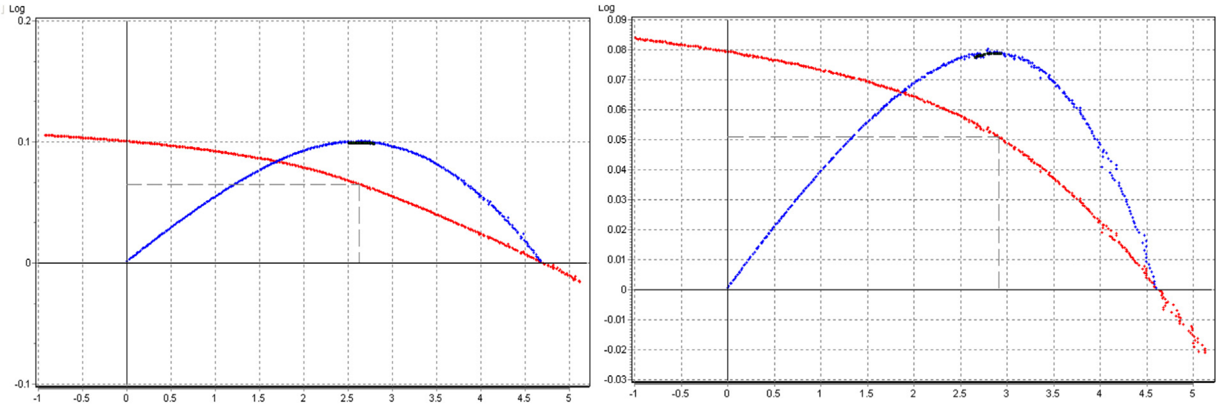

Fig. 6. Example of MP-37 I–V (red curve) and power (blue curve) characteristics after a dynamic bending test of 2500 and 7500 cycles.

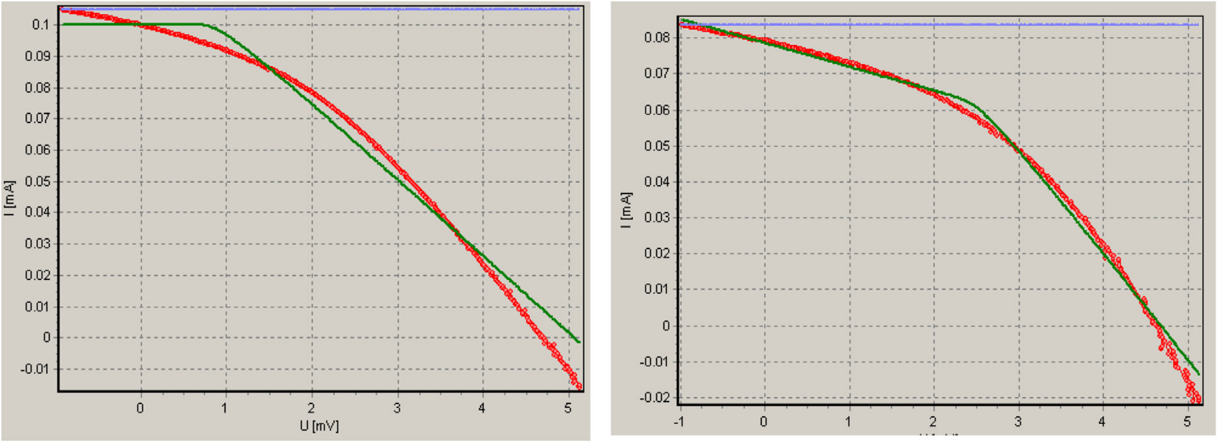

Fig. 7. Exemplary VDEM model adjusting process of measured MP-37 characteristics after a dynamic bending test of 2500 and 7500 cycles. The red curve shows real measurement results, while green curve represents model characteristics during adjustment process.

cell series resistance was observed (R_S at the level of $30\,\Omega \div 40\,\Omega$ in each case). Rapid drop of the efficiency and short circuit current of the cell is mostly caused by a shunt resistance drop. In the tested samples this value decreased from the value higher than $14\,\mathrm{G}\Omega$ to only $118\,\Omega$ after 7500 bends. This phenomenon may be explained by micro cracks of the TCO and active layers of the cell which are responsible for internal short circuits within the cell structure. Further experiments will be undertaken for morphology characterization of this mechanism, as well as for the replacement of this structure with an organic-based TCL emitter contact system.

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