Investigation of Electrical Characteristics Dependency of Roll-to-Roll Printed Solar Cells with Silver Electrodes on Mechanical Tensile Strain

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***Abstract*—In this work we have studied the effects of the tensile mechanical strain on the electrical behavior of a roll-to-roll printed solar cell module with silver electrodes. After applying the strain along the length of the solar module, its current-voltage curves were measured in dark and under light illumination conditions. By electrical parameters extraction of the curves in both conditions, valuable information was achieved which proved that the dark and light parameters are in good agreement with each other and can each be used as a means to evaluate the solar cells. Electrical parameters like series resistance and power conversion efficiency, all show improvements for moderate tensile strain levels. The power conversion efficiency had about 3.8% improvement after applying 2400 με tensile strain. This is due to the polymer chains alignment in the direction of the applied tensile strain. However, higher strain levels damaged the interfaces among the solar cells' layers. These broken bonds created a high density of defect states and thus reduced the electrical performance of the solar cell. This research showed that the solar cell under the test can be mechanically deformed under moderate strains while showing a better electrical performance. So these cells are a suitable choice for applications in which the cells are used under a mechanical tensile strain.**

***Index Terms*—Dark characteristics, light characteristics, organic solar cells, tensile strain**

I. Introduction

ORGANIC Solar Cells (OSCs) are well-known as low cost photovoltaic devices. Despite their low efficiency and scant life time, their advantages have made them popular, likely to precede the silicon based solar cells in the commercial market [1]–[8]. The advantages of the organic materials is not limited to just low cost manufacturing. One of the most important features of these materials is the mechanical flexibility which has let them to be not only a better, but maybe the exclusive alternative for some applications in comparison with the silicon electronic devices [9]–[13]. So it is necessary to understand the mechanical properties of the organic materials and study the effects of the mechanical strain on electrical behavior of the OSCs [14]; hence a growing number of researches have been done on single solar cells in this aspect [15]–[20]. For example M. Kaltenbrunner *et al.* produced ultrathin OSCs and studied their flexibility by creating compression on the cells and measuring the electrical properties [21]. Some researchers even took advantage of the changes in the electrical performance to detect the mechanical strain in strain sensors [22], [23].

But just a few works are done studying the effects of mechanical strain on electrical behavior of whole OSC modules. In our previous works we have studied the mechanical strain effects on the electrical properties of roll-to-roll printed OSC modules in dark condition. We succeeded to obtain some information about the defect states and mobility changes in the OSC modules and the important role of the electrode materials was studied. It was shown that the electrode mechanical properties such as brittleness or Young's modulus can affect the electrical behavior and can even mask the effects of the other constructing layers of the OSC. For the OSC modules with carbon electrodes, the mechanical strain was damaging the modules even at low value of applied strains while in the modules with Ag grid electrodes, moderate strains improved their conductivity. Furthermore, the effects caused by the strain were more reversible in the latter modules [24]. M. Finn *et al.* also studied the mechanical stability of two OSC modules with different electrodes by bending and torsion tests. They represented the PCE changes and reported similar results for the modules [25]. We also used the flicker noise as another way for evaluation of the OSCs and the achieved results confirmed the previous studies [26].

In this research, we do a thorough investigation on an OSC module with silver electrodes which had shown slight reversible conductivity improvement after applying moderate strain levels. Since the performance of a solar cell is more meaningful when it is exposed to light, this time the module is studied both in dark and under light illumination conditions. The OSC module is mechanically stretched along its length and electrically characterized by extracting the main electrical parameters of the OSC including the series and parallel resistances, PCE, open circuit voltage (V_{oc}), short circuit current (I_{sc}) and so on. The obtained results from dark and light

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conditions are compared, discussed and a consistency is observed. It is seen that the OSC modules with silver electrodes experiences a 3.8% improvement in PCE under moderate strain levels up to 2400 με and degrades with higher levels of strain.

II. Test Procedure

We used an organic photovoltaic (OPV) module which was made of 8 organic solar cells connected in series. The stated PCE was 4.0% and the structure of the consisting layers is depicted in Fig. 1 [27]–[29]. We also made a metal holder in order to apply a uniform mechanical strain to the solar module along one direction [24]. The standard air mass global AM1.5G light was generated using a solar simulator and at last, current-voltage (I-V) measurements were done by a Keithley 2400 source meter. Fig. 2 shows the solar module fixed in the holder, under the illumination by the solar simulator.

The test procedure was to add the mechanical strain to the solar module step by step and measure the I-V curves in both light and dark conditions, in each step. The amount of strain added in each step was 2000 με and was continued until step 40, at which the solar module started to show severe electrical malfunction due to high mechanical stress. In order to give some time to the polymers' morphology to rearrange and reach to a stable state, I-V measurements in each step were done 3 minutes after applying the strain. It also should be noted that during the whole test the ambient temperature was constant (room temperature ~24°C). A slight temperature increment on the surface of the solar module was observed during the light illumination, which can be ignored since it was the same in all steps.

III. Results and Discussion

The current of a solar cell as a function of its voltage can be obtained using

$$I = I_s\left(exp\left(\frac{\beta}{\eta}(V - IR_s)\right) - 1\right) + G_p(V - IR_s) + I_{ph} \qquad (1)$$

where I_s is the saturation current, $\beta = e/kT$ is the inverse thermal voltage, η is the ideality factor, R_s is the series resistance, G_p is the shunt conductance and I_{ph} the generated photocurrent. We used the Werner method and extracted these electrical parameters from the dark I-V curves of the solar module [30]. Since no photocurrent is generated when the solar

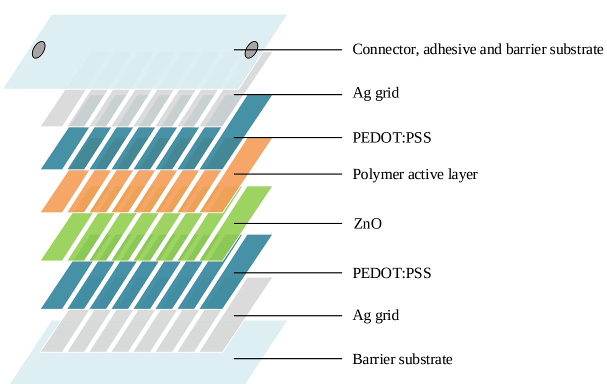

Fig. 1. The constructing layers of the solar cell module under the test.

cells are not exposed to light, I_{ph} equals zero in dark condition. The other four parameters (*i.e.* R_s, G_p, η and I_s) can be extracted from a single dark I-V curve that will give many information about the defect states and morphology of the solar cells. The changes of R_s and $R_p = 1/G_p$ (shunt resistance) with mechanical strain increment is displayed in Fig. 3. As can be seen in this plot, R_s has two different behaviors with increasing the mechanical strain. For more than half of the strain steps (about 44000 με), R_s experiences a slight decrease. But after that, it starts to increase with applied strain. Previous studies have shown that applying the mechanical strain can make the back bone of the polymer to align in the direction of the strain [31], [32]. This makes it possible for the charge carriers to move a longer distance along a single chain which is much faster than hopping from chain to chain [14]. In general, improving the alignment of the conjugated polymers has positive effect on the mobility of the charge carriers. Researchers have used different methods such as tensile strain, thermal annealing, controlled active layer growth speed and so on, to improve the mobility by increasing the crystallinity of the polymers [33], [34]. But as mentioned in the previous section, in this study we have focused on the role of electrodes when the device is under stress. The total variations of electrical characteristics are analyzed considering the effects of strain on the electrodes as well as the active layer. Interested readers can look up more detailed information about the mechanism of conductivity in the strained devices in [14], [24], [26], [31], [32]. So moderate tensile strain can improve the mobility and thus reduce the R_s due to the inverse dependency of the series resistance to the

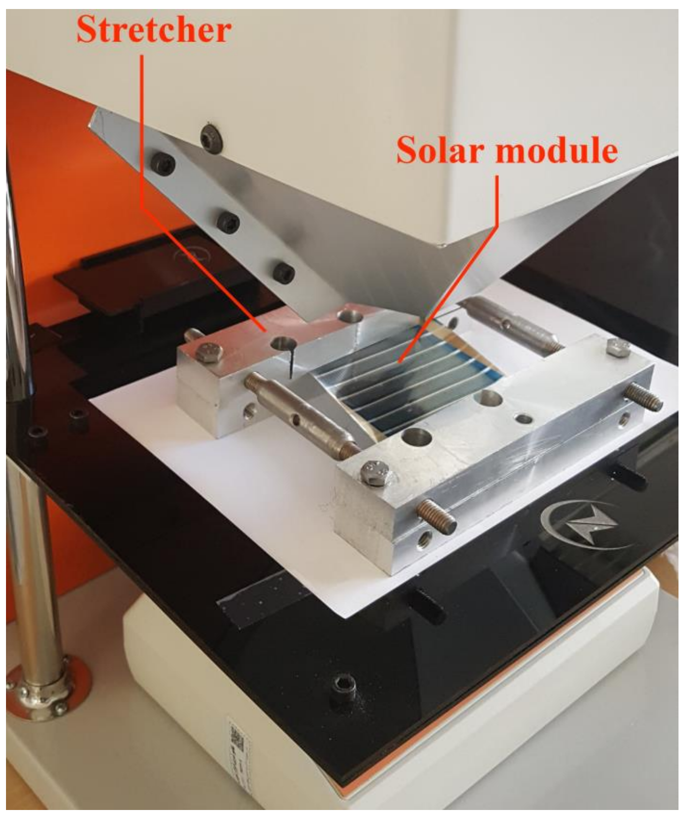

Fig. 2. The solar cell module fixed in the metal holder and placed under the illuminated light of a solar simulator.

mobility [35]. But by applying higher strains to the OSC modules, the constructing layers of the modules –especially electrodes– start to detach from each other which results in creating defect states in the interfaces. These defect states will decrease the mobility by acting as traps for the charge carriers [24]. More than that, since the resistance is proportional to the length of the material, increasing the length of the layers and the electrodes with large strain levels, causes an increment in R_s. R_p in comparison has an almost continuous trend and an inverse dependency to the tensile strain. Applying the strain and increasing the length of the OSC modules reduces the thickness of the layers. This will create parallel conductive paths which means a decreased shunt resistance in the cells. Finally, I_s and η had no significant change with the tensile strain. In previous researches also R_s has been the dominant parameter and changes in I_s and η were not so large [36], [37].

Analyzing light I-V curves also gives useful information about the electrical behavior of the strained solar cells. For example, R_s and R_p extracted from the light I-V curves differ from those of the dark I-V curves, however, they show a similar trend of changes versus applied tensile strain, see Fig. 4. Although V_{oc} did not show considerable changes with increasing the strain, I_{sc} showed some slight variations with the applied strain which are displayed in Fig. 5. For the initial steps, as the defect states density is low, the positive effect of the strain alignment and increasing the mobility is seen as a slight improvement in I_{sc}. But for the next steps, decreasing the mobility, resulted from the large density of the defect states, causes I_{sc} to decrease by increasing the strain. In addition to the conductivity, the exciton generation process is also affected by the strain. As it was mentioned previously, stretching the solar cell makes it thinner thus less active layer polymer will be available per unit area of the incident light. This leads to lower density of generated excitons and clearly lower light current density. M. Kaltenbrunner *et al.* saw the opposite effect for when the solar cell was compressed [21].

Besides V_{oc} and I_{sc} on the I-V plot of the solar cells, it is also important to study the shape of the curve in the region between these two points, which indicates the PCE and fill factor (FF) of the solar cell. J. Servaites *et al.* showed that the series resistance has a major effect on the PCE and FF of the solar cell [36]. Increasing the series resistance changes the shape of the curve by decreasing the contribution of the exponential part in (1) and transforming it to a linear curve as demonstrated in Fig. 6(a). In this plot, the I-V curve of the solar cell under test, with no applied strain is compared with that of the last step with the maximum strain (78000 με). It clearly shows the effect of R_s increment on the I-V curve shape. For better demonstration, the measured results around the maximum power point are zoomed in Fig. 6(b) for different steps of applied strain. It can be seen that the shape of the I-V curve follows the R_s changes shown in Fig. 3. At moderate strain levels, the curve gets closer to a rectangular form, but at higher applied strains, it is pushed

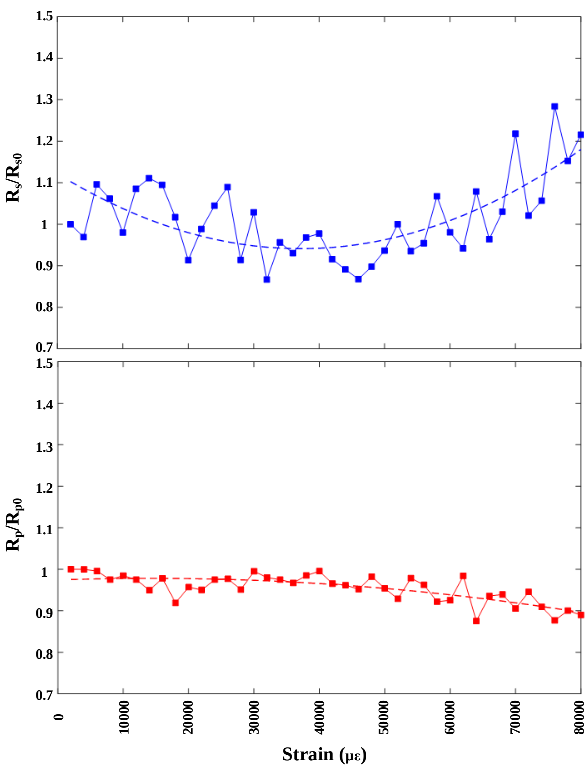

Fig. 3. Changes of the series and shunt resistance with the tensile strain. The resistances are normalized to the initial values at the beginning of the test. The dashed lines are the corresponding interpolation curves.

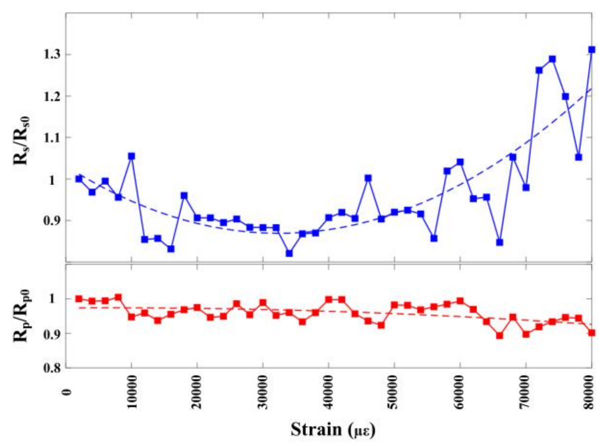

Fig. 4. Changes of the normalized series and shunt resistance with the tensile strain. Resistance values are extracted from light I-V curves. The dashed lines are the corresponding interpolation curves.

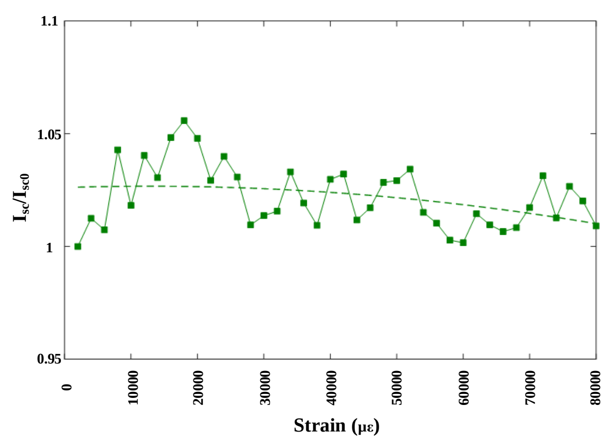

Fig. 5. Changes of the normalized short circuit current with the tensile strain. The dashed line is the corresponding interpolation curve.

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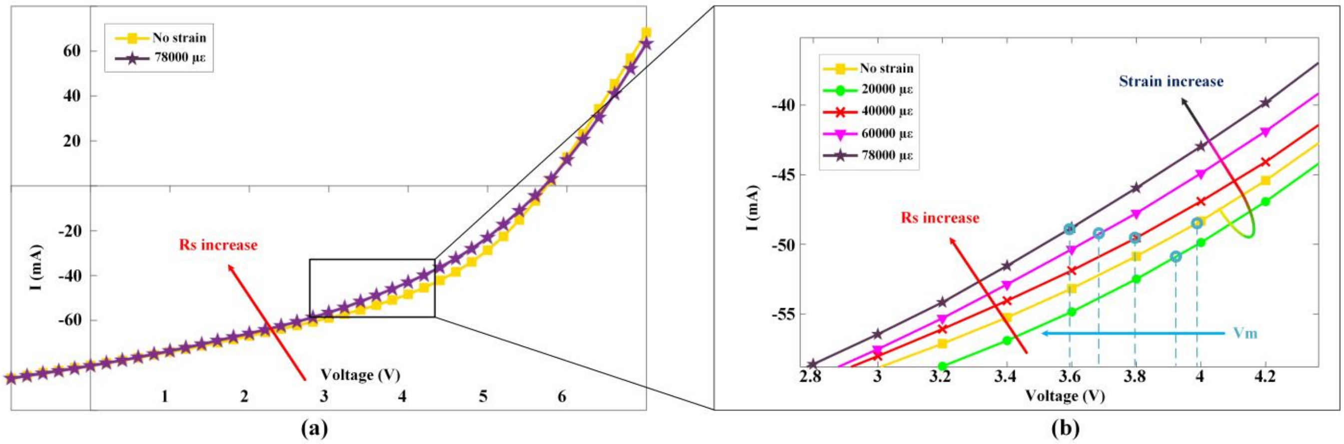

Fig. 6. (a) I-V curves of the solar cell module under the light illumination with no applied strain and with 78000 με strain at the final step. (b) Zoomed plot of the results for five different strain steps applied to the solar module under test.

toward a linear shape. This changes PCE as shown in Fig. 7 as was expected from the dark analysis. Improvement of the mobility in the initial steps causes a 3.8% PCE increment and increasing R_s at higher strains results in a PCE decrement. Although R_s decreases for steps up to 20, PCE improving stops at a few steps sooner. This can be explained considering the other parameters variations, mainly the decrement of the R_p and I_{sc}. It is also obvious in Fig. 6(b) that the maximum power points (V_m) of the I-V curves of the strained solar cell modules move toward lower voltages by increasing the applied mechanical strain that is also a result of changing the shape of the I-V curve. In this test, by applying 80000 με tensile strain in the final step, V_m of the solar module is reduced by ~0.4 V. So even for the same or improved PCE under the mechanical strain, the optimum operating point of the solar cells may vary with the strain. Finally, FF versus applied strain is depicted in Fig. 8 which shows a clear descending trend. FF is calculated using

$$FF = \frac{(PCE)\times P_0}{I_{sc}V_{oc}} \tag{2}$$

in which P_0 is the incident light power. In this test, P_0 and V_{oc} are constant values and according to Figs. 5 and 7, I_{sc} and PCE have almost a similar course of changes but in different amounts. For the first few steps, I_{sc} increment is more than PCE and after that, PCE decrement is dominant in comparison with I_{sc} decreasing. Therefore, according to (2), in both regions, variations of FF versus mechanical strain shows a negative slope as seen in Fig. 8.

IV. Conclusion

We did an in-depth study on the effects of the mechanical tensile strain on the electrical behavior of the OSC modules. We used a metal holder made by the authors to apply uniform tensile strain to a roll-to-roll printed solar module consisted of 8 organic solar cells with silver electrodes connected in series. Applied strain was added step by step and in each step, I-V curves of the solar module were measured in both dark and light conditions. Analyzing the dark I-V curves gives useful information about the structure and electrical behavior of the solar cells by which the performance of the cell can be estimated. And curves plotted under light illumination are in agreement with the estimations from dark analysis. The results of this study showed that although high strain levels degrades the electrical behavior of these OSCs, moderate tensile strain can be harmless to them and even can improve their performance slightly. So these solar modules can be used for applications that need steady electrical performance in bending

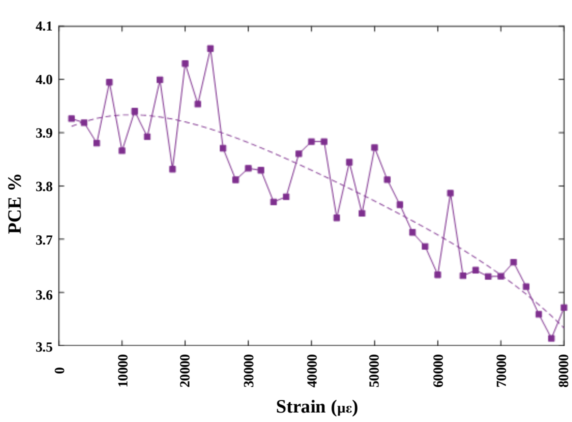

Fig. 7. Changes of PCE with the tensile strain. The dashed line is the corresponding interpolation curve.

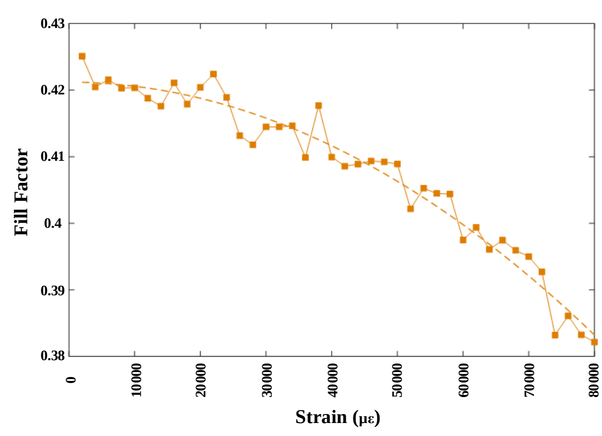

Fig. 8. Variations of FF versus the applied tensile strain. The dashed line is the corresponding interpolation curve.

or straining such as flexible displays, wearable electronics and so on. Electrical characterizations of this kind help to discover the optimum conditions in which the solar cells should be utilized. Provided results give a better understanding on the morphology and structure of the solar cells, too. In addition, they help modelling the device and they are essential for reliability and lifetime investigations.

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