ISSN (Online) : 2319 - 8753
ISSN (Print) : 2347 - 6710

International Journal of Innovative Research in Science, Engineering and Technology

Volume 3, Special Issue 3, March 2014

2014 International Conference on Innovations in Engineering and Technology (ICIET'14)
On 21st & 22nd March Organized by

K.L.N. College of Engineering and Technology, Madurai, Tamil Nadu, India

Effect of Stress on the Performance of Silicon Solar Cell

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Abstract— In this paper the effect of stress on the performance of silicon solar cell (photovoltaic device) is studied using TCAD simulations. The solar cell performance metrics such as open circuit voltage and short circuit current are studied for various stress levels. It was observed that the compressive stress enhances the open circuit voltage, whereas tensile stress improves the short circuit current through mobility change. It is also observed that the impact of tensile stress on life time enhances both the open circuit voltage and short circuit current.

***Keywords*—** solar cell, mobility, minority carrier lifetime, compressive stress, tensile stress.

I. INTRODUCTION

In today's world most valuable renewable energy resource is the solar energy because of its green technology. Light may be viewed as consisting of "packets" or particles of energy, called photons. A normal PN diode is modified to operate as a solar cell in which Silicon is the absorbing material. Photo voltaic (PV) devices (solar cells) are unique in that they directly convert the incident solar radiation into electricity, with no noise, and less pollution.

Exposing solar cell to sunlight generates electron hole pairs due to the absorption of photons. Electron hole pair is possible when the incoming photon energy is greater than the band gap of silicon (1.12 eV) so that the electron reaches a higher energy level leaving a hole in the valence band. The charge carriers tend to recombine immediately but it has to be separated quickly and is made possible by the built in electric field in PN junction device.

Strained silicon has the ability to improve the metal-oxide-semiconductor field-effect-transistor (MOSFET) performance [1]. Stress has the ability to change both mobility [2] and lifetime [3] and hence changing the performance of the device. Increase in mobility enhances the silicon device due to increase in conductivity. Increase in lifetime takes more time for charge carriers to recombine thereby possibility of collecting more amounts of carriers.

The mobility model for silicon under different stress/strain [5] conditions is given by equation (1). $\hat{\mu}_{n,uns}^{(i)}$ unstrained electron mobility tensor of the conduction band in Si with the corresponding electron concentration ($n_{str}^{(i)}$) in the i[th] valley pair in strained-Si.

$$\hat{\mu}_n^{tot} = \sum_{i=1}^{3} p^{(i)}.\hat{\mu}_{n,uns}^{(i)}, \quad p^{(i)} = \frac{\eta_{str}^{(i)}}{\sum_{i=1}^{3}\eta_{str}^{(i)}} \qquad (1)$$

$$\eta_{str}^{(i)} = N_C^{(i)}.\exp\left[\frac{\Delta E_C^{(i)}(y)}{k_B T}\right] \qquad (2)$$

$\eta_{str}^{(i)}$ is calculated for non degenerate doping concentration with $N_C^{(i)}$ as the density of states and $\Delta E_C^{(i)}(y)$ as the energy shift for the i[th] valley, respectively. k_B and T denote the Boltzmann's constant and ambient temperature, respectively. The shift in energies of the conduction band valleys is given by

$$\Delta E_C^{(i)} = \Xi_d\left(\varepsilon_{xx}+\varepsilon_{yy}+\varepsilon_{zz}\right)+\Xi_u\varepsilon_{ii}, \quad i = x, y, z \qquad (3)$$

with Ξ_d and Ξ_u as the dilatation and shear deformation potentials for the conduction band and the ε_{ii}'s are the diagonal components strain tensor expressed in the principal coordinate system. The above expression is valid for arbitrary stress/strain conditions, uniaxial/biaxial strain.

In this paper, silicon solar cell is designed using TCAD Simulator and its characteristics are studied for various values of stress. Short circuit current (J_{sc}) and open circuit voltage are taken as metrics (V_{oc}) [2], [3]. The knee voltage for our PN junction structure is 0.67 V. Section 2 discusses about the simulator and simulation methodology. Section 3 deals with the results obtained from the simulations and finally the conclusions are provided in section 4.

II. Simulation Methodology

Sentaurus TCAD simulator from Synopsys is used to perform all the simulations. This simulator has many modules and the following are used in this study.

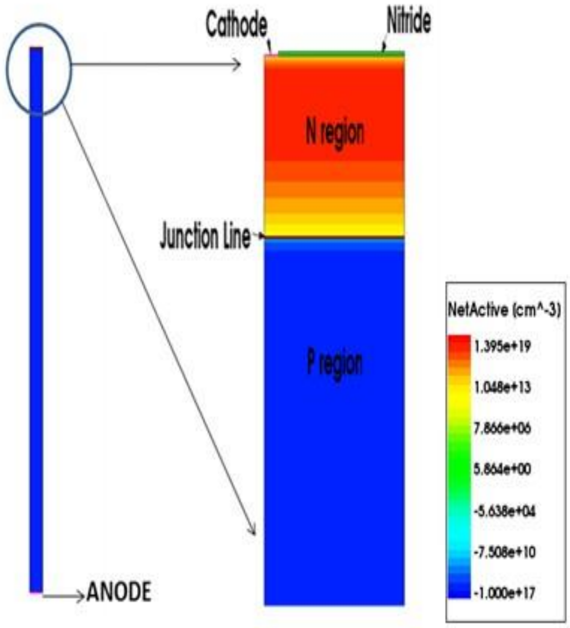

Fig. 1 Structure of Solar Cell

TABLE I
DEVICE DIMENSIONS AND DOPING

Attributes	N Region	P Region
Thickness(μ m)	0.5	299.5
Doping Concentration(cm^{-3})	1×10^{19}	1×10^{17}
Total Width(um)	1	1

- Sentaurus Process (SPROCESS): To create the device structure, to define doping, to set contacts, and to generate mesh for device simulation. This is similar to fabrication process steps.
- Sentaurus device simulator (SDEVICE): To perform DC simulations
- Inspect and SVisual: To view the results

The physics section of sdevice includes the appropriate models for illuminating the solar cell. Sentaurus process simulates the illuminated I-V curve using the optical solver from File. In this project, AM1.5g solar spectrum is used. The spectra files are text files consisting of two data wavelength (um) and intensity (W/cm^2). An illumination window is used to confine the incident light to a certain part of the 2D solar cell structure and is specified in the Optics-Excitation-Window section.

The structure of solar cell using SPROCESS is shown in Fig. 1 and their corresponding dimensions in Table I. The p type region is thick in order to absorb as much light as possible and lightly doped to improve diffusion length. The n type region is heavily doped to reduce sheet series resistance and should be thin to allow as much light as possible to pass through to the p region. Carrier collection from the n region is negligible because of high recombination in this heavily doped layer [4].

The device is formed by implanting arsenic on the p type substrate with a dose of 1×10^{14} cm^{-2} and subsequent energies of 100 keV, 260 keV, 320 keV such that the junction line forms at 0.5 μ m separating the n and p region. To increase the absorption rate, an antireflection coating nitride layer is formed on the top of N region. Finally contacts and meshing is done.

III. Results and Discussion

Fig. 3 depicts the I-V curve of the solar cell without any stress embedded into the solar cell. Commercial solar cells have short-circuit current density between about 28 mA/cm^2 and 35 mA/cm^2. The short circuit current density (J_{SC} = 31.21 mA/cm^2) is the maximum current from this solar cell and it occurs when the voltage across the device is zero. The open circuit voltage (V_{OC} = 0.6509V) is the maximum voltage and it occurs when the net current through the device is zero. When the amount of incoming photons increases the short circuit current and open circuit voltage also increases.

Fig. 2 shows the illuminated solar cell for 0.1 W/cm^2 and 0.05 W/cm^2 intensity.

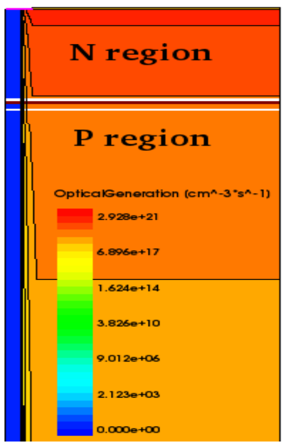

Fig. a

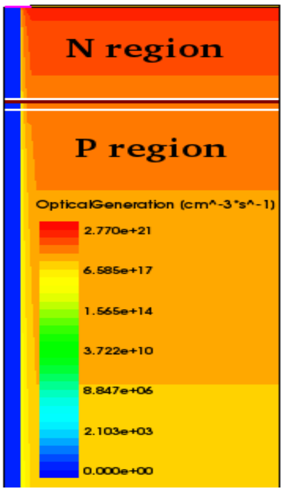

Fig. b

Fig. 2 Illuminated Solar Cell (a) for 0.1 W/cm^2 intensity (b) for 0.05W/cm^2 intensity

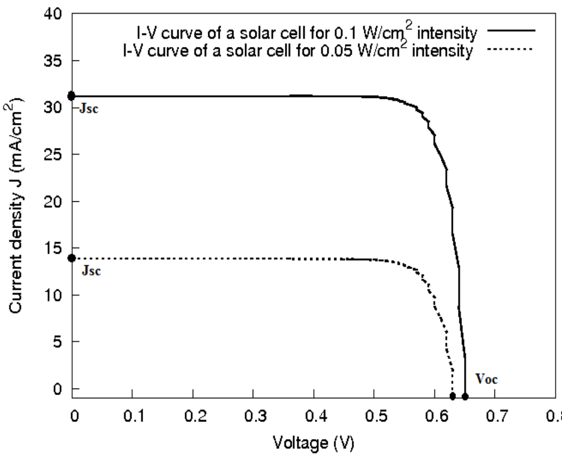

Fig. 3 I-V curve of an Illuminated Solar Cell

Fig. 4 shows the electron hole density rate versus thickness for 0.1 W/cm^2 intensity. It is observed that the optical generation rate decreases as a function of depth because the light absorbed gets reduced as we go deep into the device. Fig. 5 shows the electron hole density versus thickness for 0.05 W/cm^2 intensity. It is observed that for 0.05 W/cm^2 intensity the optical generation rate is less than 0.1 W/cm^2 intensity.

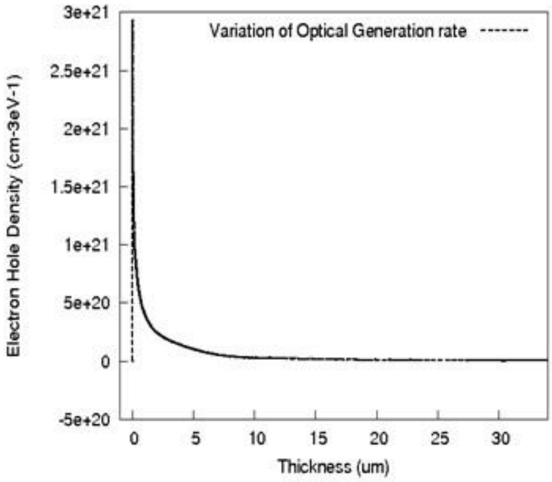

Fig. 4 Electron Hole Density (0.1 W/cm^2 intensity) as a function of thickness

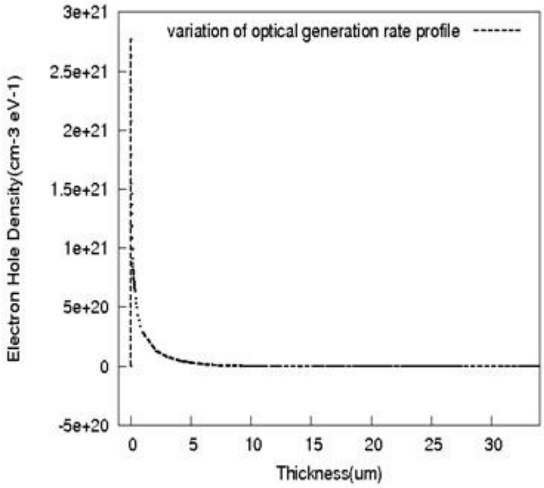

Fig. 5 Electron Hole Density (0.05 W/cm^2 intensity) as a function of thickness

Stress affects the mobility and life time in a material. The study here is split into 3 cases. In the case 1, the impact of stress on mobility alone is considered and the performance of solar cell was investigated. In the case 2, the impact of stress on life time is considered and in case 3, both the effects are considered simultaneously. In Fig. 6 depict the stress versus mobility and stress versus life time graphs. They are reproduced from [2], [3].

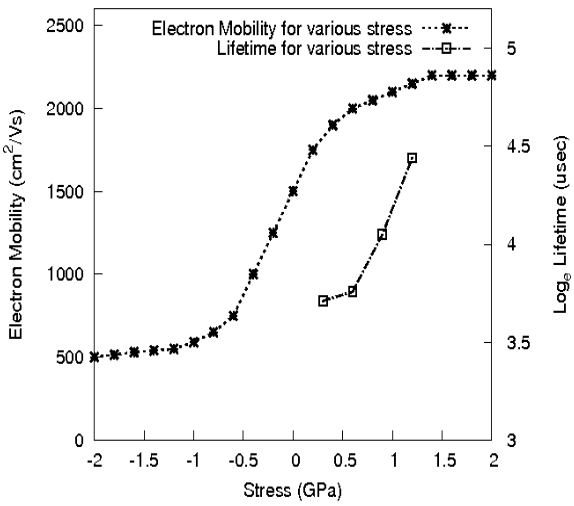

Fig. 6 Effect of stress on mobility and lifetime

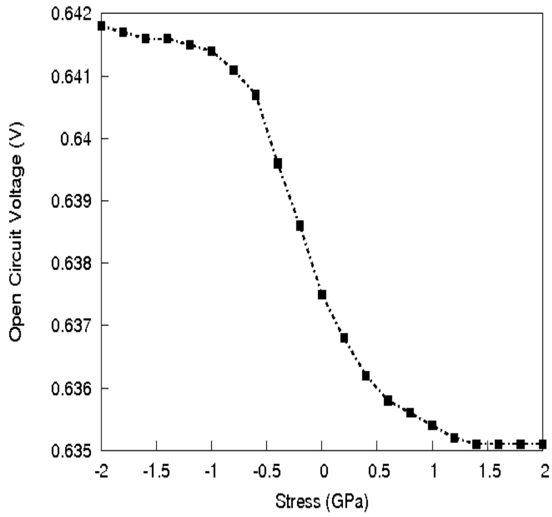

Fig. 8 Stress vs V_{oc} considering the impact of mobility alone

A. Case 1

The effect of stress on the mobility of solar cell has been studied and the Fig. 7 and Fig. 8 depict the stress versus J_{SC} and V_{OC} respectively, assuming the impact on mobility alone. The range of the stress values considered for mobility is 0-2 GPa, both tension and compression. It is observed that the increase 0in tensile stress improves the J_{SC} and maximum at 1.4 GPa (Fig. 7; 34.43 mA/cm^2) and tends to saturate for stress beyond a certain level. It is also observed that the compressive stress (in the range 0 – 2 GPa) enhances the V_{oc} and maximum at 2 GPa (Fig. 8; 0.6418 V). Fig. 9 shows the (J_{SC} x V_{OC}) as a function of stress, considering the stress impact on mobility. It can be observed from Fig. 9 that the maximum power density (21.93 mW/cm^2) is attained for stress of 0.4 GPa.

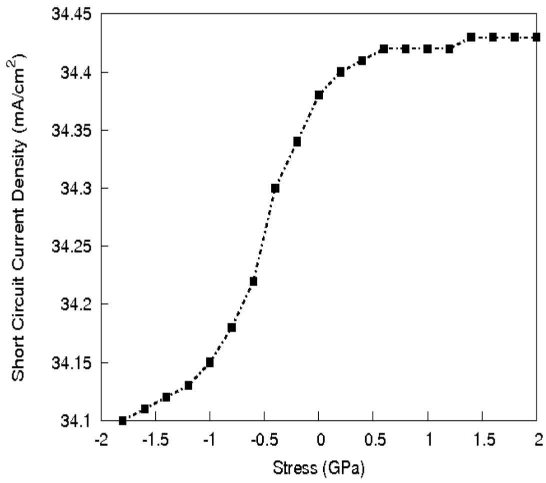

Fig. 7 Stress vs J_{SC} considering the impact of mobility alone

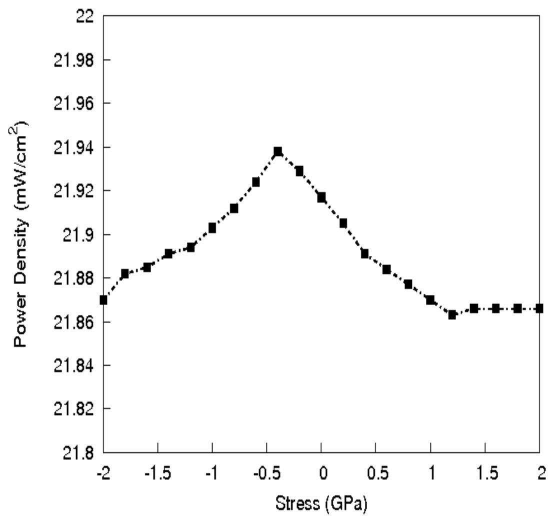

Fig. 9 Stress vs Power Density considering mobility alone

B. Case 2

Fig. 10 and Fig. 11 show the stress versus short circuit current density and open circuit voltage, assuming the stress impact on life time alone. The range of the stress values considered in Fig. 10 and Fig. 11 is 0-1.2 GPa, tension. The increase in tensile stress causes an increase in J_{SC} as well as in V_{OC}. Fig. 12 shows the (J_{SC} x V_{OC}) as a function of stress, considering the stress impact on mobility. It can be observed from Fig. 12 that the maximum power density (21.75 mW/cm^2) is attained for stress of 1.2 GPa.

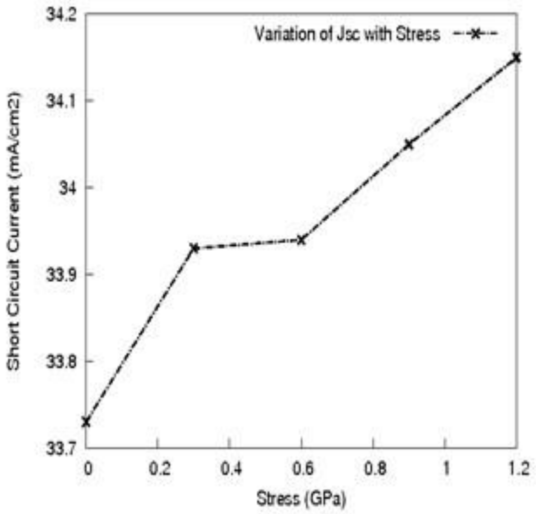

Fig. 10 Stress vs J_{SC} considering the impact of life time alone

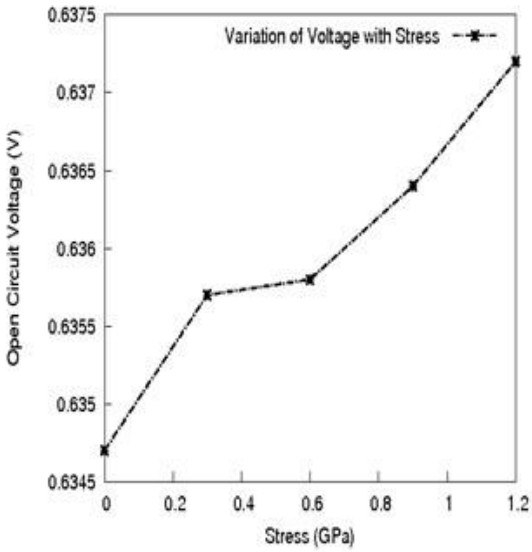

Fig. 11 Stress vs V_{OC} considering the impact of lifetime alone

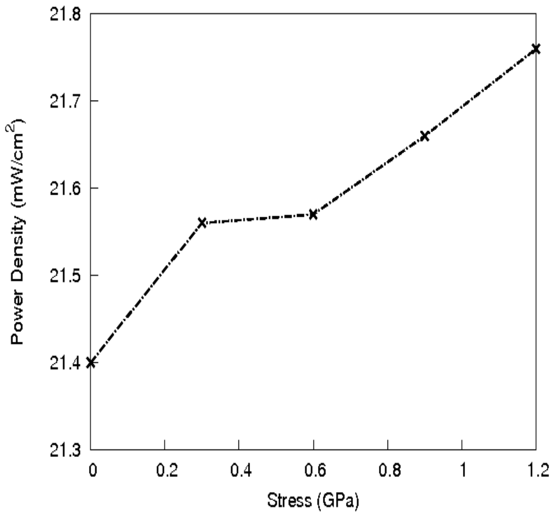

Fig.12 Stress vs Power Density considering lifetime alone

C. Case 3

Here the impact of stress on mobility and life time are considered simultaneously. The range of the stress values considered for this study is 0.3-1.2 GPa. The results of this study are shown in Fig. 13 and Fig. 14. While the tensile stress enhances the J_{SC} monotonically the V_{OC} shows a different behaviour with respect to tensile stress i.e the V_{OC} decreases initially and then increases as the stress increases. Fig. 15 shows the (J_{SC} x V_{OC}) as a function of stress, considering the stress impact on mobility. It can be observed from Fig. 15 that the maximum power density (21.74 mW/cm^2) is attained for stress of 1.2 GPa.

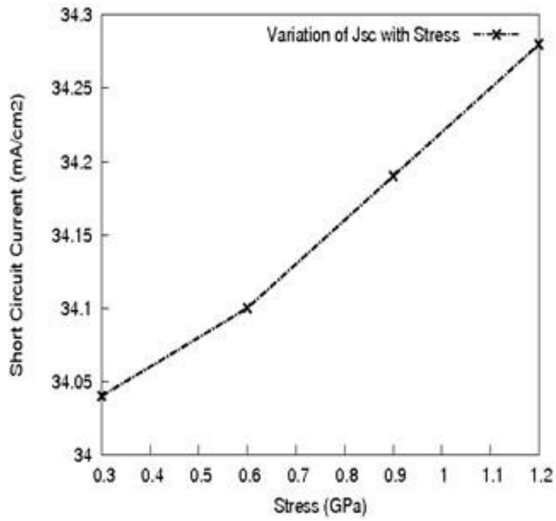

Fig. 13 Stress vs J_{SC} considering both mobility and lifetime

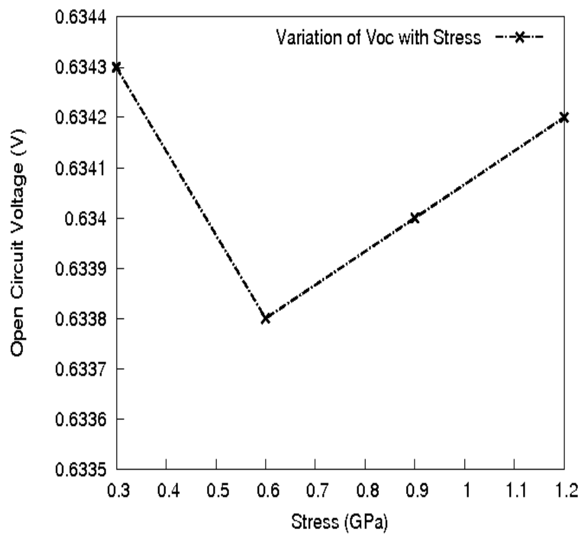

Fig. 14 Stress vs V_{OC} considering both mobility and lifetime

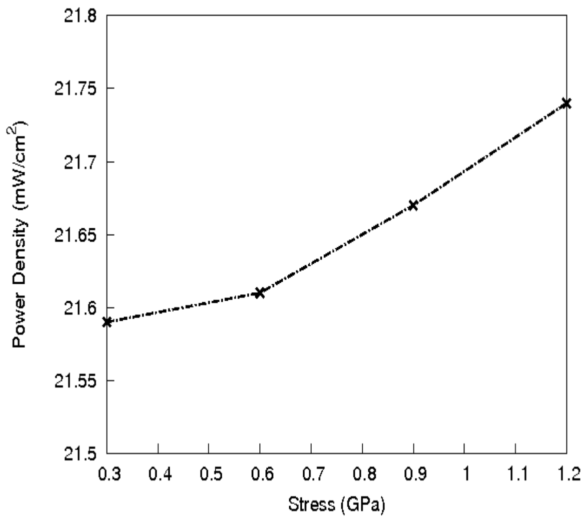

Fig. 15 Stress vs Power Density considering both mobility and lifetime

IV. CONCLUSION

In this paper, we have investigated the performance stressed solar cell, short circuit current density and open circuit voltage. Since, the stress can affect the mobility and life time three different cases are considered namely impact of stress on mobility alone, impact of stress on life time alone and the impact of stress on both mobility and life time simultaneously. Depending on the stress values the V_{OC} may be better or worser. It is obvious that the change in mobility and lifetime due to stress (both tensile and compression) improves the performance of the solar cell metrics.

ACKNOWLEDGMENT

This work is supported by Defense Research Development Organization (DRDO), Government of India.

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