Electronic Supplementary Material (ESI) for Journal of Materials Chemistry A
This journal is © The Royal Society of Chemistry 2014

All-plastic solar cells with a high photovoltaic dynamic range

Yinhua Zhou, Talha M. Khan, Jae Won Shim, Amir Dindar, Canek Fuentes-Hernandez, and Bernard Kippelen*

Center for Organic Photonics and Electronics (COPE), School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332

*Author to whom correspondence should be addressed; electronic mail: kippelen@ece.gatech.edu

Supporting information:

The trend of the FF as a function of light irradiance can be analyzed using a single diode equivalent circuit model described by the following equation: [1]

$$J = \frac{1}{1+R_S/R_P}\left[J_S\left\{\exp\left(\frac{V-JR_SA}{nkT/q}\right)-1\right\}-\left(J_{ph}-\frac{V}{R_PA}\right)\right], \quad (1)$$

where R_S is the series resistance, R_P is the shunt resistance, J_S is the reverse saturation current density, A is the solar cell area, q is the elementary charge, k is Boltzmann's constant, T is the absolute temperature, n is the ideality factor of the diode, and J_{ph} is the photogenerated current density. Under ideal conditions where $\mathrm{R}_s = \frac{1}{R_p} = 0$, an upper-limit for the fill factor, FF_0, is defined as

$$\mathrm{FF}_0 = \frac{v_{OC} - \ln\left(v_{OC}+0.72\right)}{v_{OC}+1} \quad (2)$$

where $v_{OC} = \frac{eV_{OC}}{nkT}$.

The *J-V* characteristics were measured as a function of light irradiance. In order to analyze data in the context of equation (1), experimentally measured photovoltaic parameters are plotted as a function of J_{SC} instead of irradiance. Fig. 3b in the main text (for completeness here also included as Fig. S1a) shows that V_{OC} follows a linear dependence on the logarithm of J_{SC}. According to $v_{OC} = \frac{eV_{OC}}{nkT}$ (n = 1.82 as mentioned in the main text), v_{OC} also follows a linear dependence on the logarithm of J_{SC} (in Fig. S2a). v_{OC} ranges from 5 to 18. According to equation (2), FF_0 under varying irradiance is plotted in Fig. S1c. The FF_0 increases with larger light irradiance because of larger V_{OC}, ranging from 0.55 to 0.79.

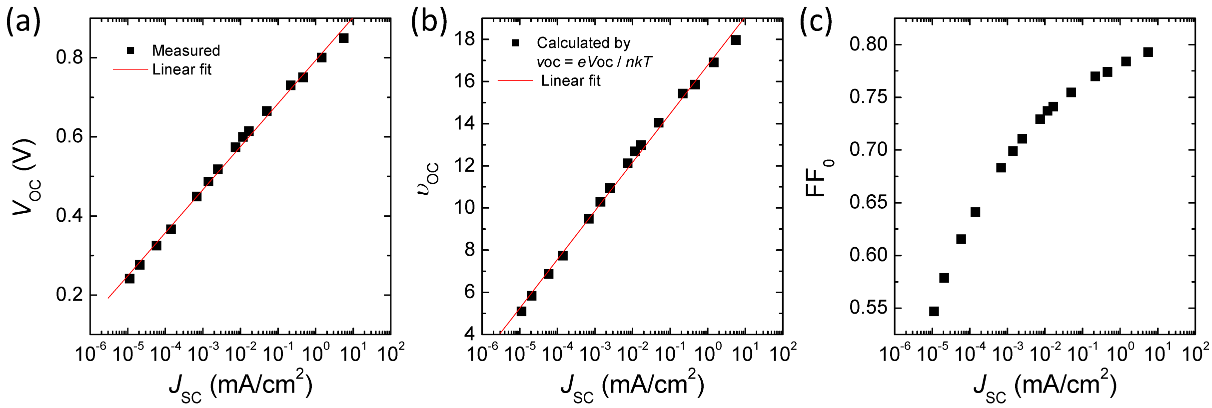

Fig. S1. Plots of V_{OC}, v_{OC} and FF_0 under varying light irradiance on a semi-logarithmic scale.

To incorporate the effects of R_S and R_P, a characteristic resistance for the device is defined as $\left(R_{ch} = \frac{V_{OC}}{J_{SC}A}\right)$ and normalized series resistance (r_S) and normalized shunt resistance (r_P) defined by $\left(r_S = \frac{R_S}{R_{ch}}\right)$ and $\left(r_p = \frac{R_p}{R_{ch}}\right)$,, *respectively*. Using these quantities, the following semiempirical expressions have been shown to be good approximations to the experimental values of FF:

$$\mathrm{FF_S} = \mathrm{FF_0}(1-1.1r_S)+0.19r_S^{\,2} \qquad \left(0 \le r_S \le 0.4, 1/r_P = 0\right), \tag{3}$$

$$\mathrm{FF_{SP}} = \mathrm{FF_S}\left\{1-\frac{(v_{OC}+0.7)}{v_{OC}}\frac{\mathrm{FF_S}}{r_P}\right\} \quad \left(0 \le r_S + 1/r_P \le 0.4\right) \tag{4}$$

Electronic Supplementary Material (ESI) for Journal of Materials Chemistry A
This journal is © The Royal Society of Chemistry 2014

Fig. S2a shows R_{CH} as a function of J_{SC}. R_{CH} varies over five orders of magnitude. $R_S A$ ranges from 47 to 70 ohm cm^2 (device area A is 4 mm^2), estimated from 0.95 - 1.0 V of the J-V characteristics. R_S slightly increases with larger light irradiance. r_S is calculated to be <0.4 (Fig. S2b) and FF_S can be calculated with the equation (3). The dependence of FF_S as a function of J_{SC} is shown in Fig. S2e. Clearly, the FF_S first increases and then decreases when light irradiance keeps increasing ranging over 5 orders of magnitude. Furthermore, the effect of R_P is also considered. r_P and r_S+1/r_P are shown in Fig. S2c and d. Again, r_S+1/r_P is less than 0.4. The FF_{SP} is calculated and shown in Fig. S2e. The introduction of r_{SP} does not change the trend of FF as a function of irradiance but slightly reduces the values of FF. Though the values of FF_{SP} (Fig. S2e) obtained by the calculation are not exactly the same as the experimentally measured values of FF (Fig. 3c), they clearly show a similar trend as a function of the irradiance.

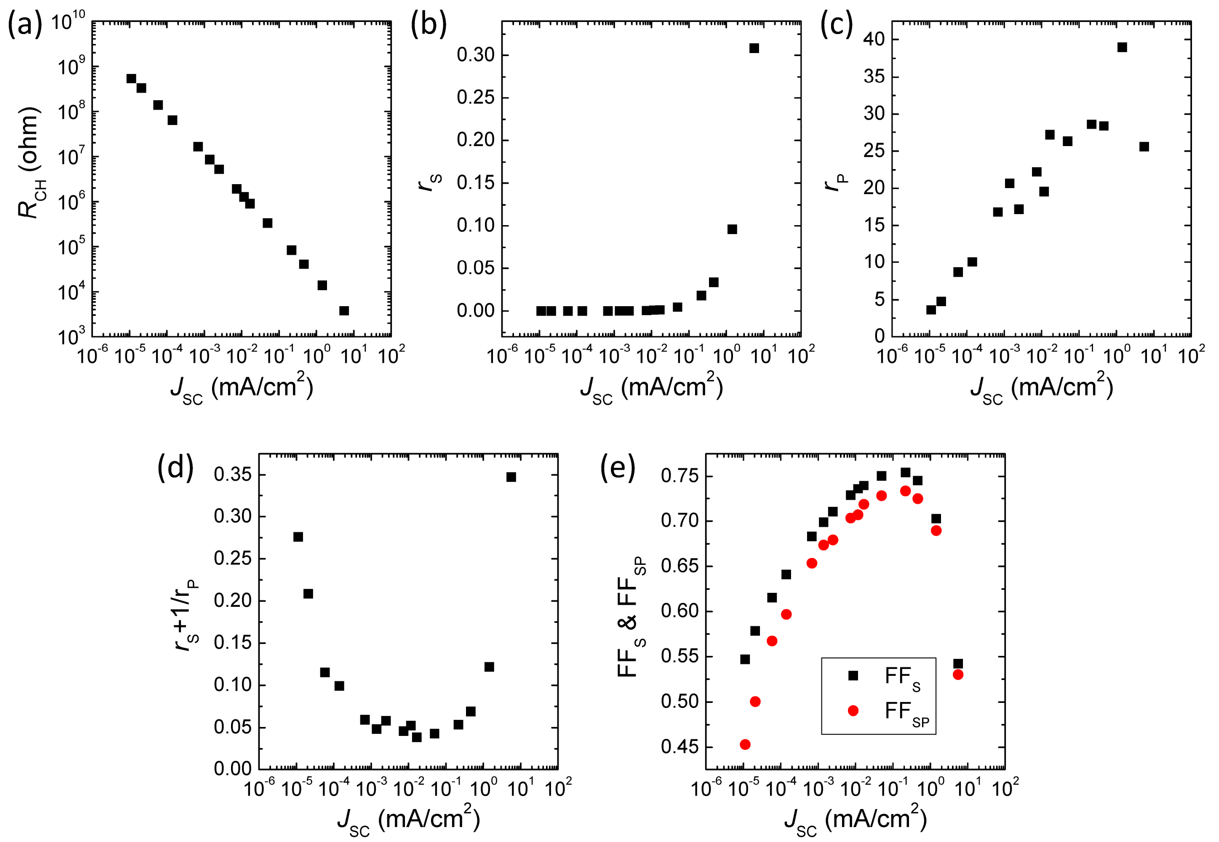

Fig. S2. Plots of (a) R_{CH}, (b) r_S, (c) r_P, (d) r_S+1/r_P, (e) FF_S & FF_{SP} under varying irradiance on a semi-logarithmic scale.

In summary, the FF increases when the light irradiance increases because of the larger V_{OC}. However, when light irradiance further increases, the FF decreases because of the larger r_S. The r_P does not change the trend of FF as a function of irradiance but reduces the values.

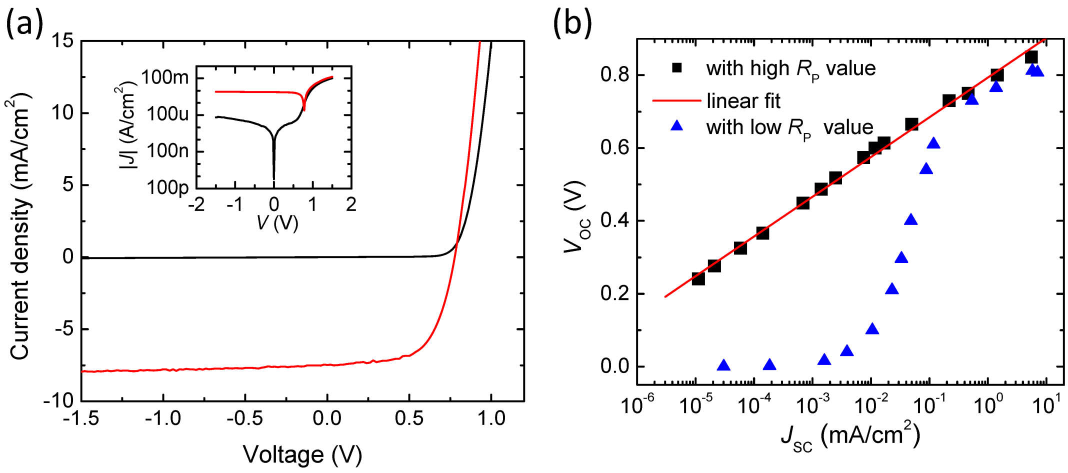

Fig. S3. (a) *J-V* characteristics in the dark and under AM1.5 100 mW/cm^2 illumination of a solar cell, fabricated by conventional spin-coating methods, having a low shunt resistance value; (b) V_{OC} as a function of J_{sc} for the spin-coated device; for comparison, the V_{OC} under varying light irradiance of an all-plastic solar cell fabricated by film-transfer lamination is also plotted, with linear fit.

Reference:

[1] S. Yoo, B. Domercq, B. Kippelen, *J. Appl. Phys.* **2005**, *97*, 103706.