# p-Supplementary Information

# High Efficiency Solar Cells from Extremely Low Minority Carrier Lifetime Substrates Using Radial Junction Nanowire Architecture

*Vidur Raj[1,*], Kaushal Vora[2], Lan Fu[1], Hark H. Tan[1,*], and Chennupati Jagadish[1]*

[1]Department of Electronic Materials Engineering, Research School of Physics and Engineering, The Australian National University, Canberra, ACT 2601, Australia

[2]Australian National Fabrication Facility, Research School of Physics and Engineering, The Australian National University, Canberra, ACT 2601, Australia

E-mail: vidur.raj@anu.edu.au; hoe.tan@anu.edu.au

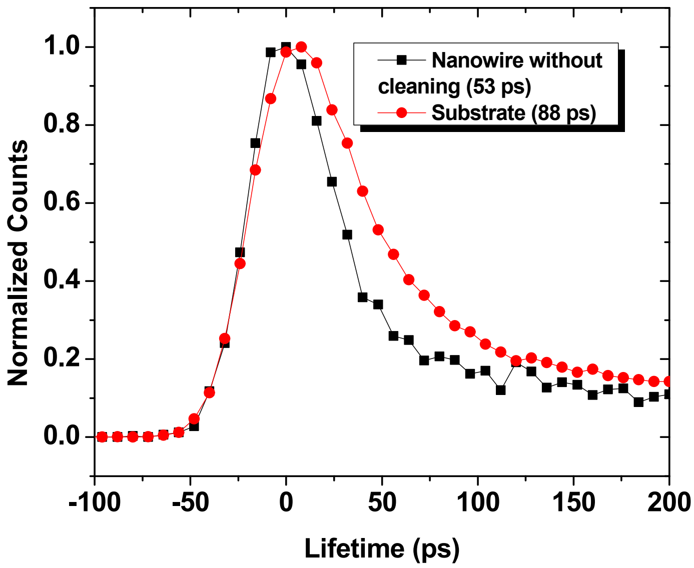


**Figure S1.** Comparative lifetime measurement on nanowire without cleaning and the substrate.

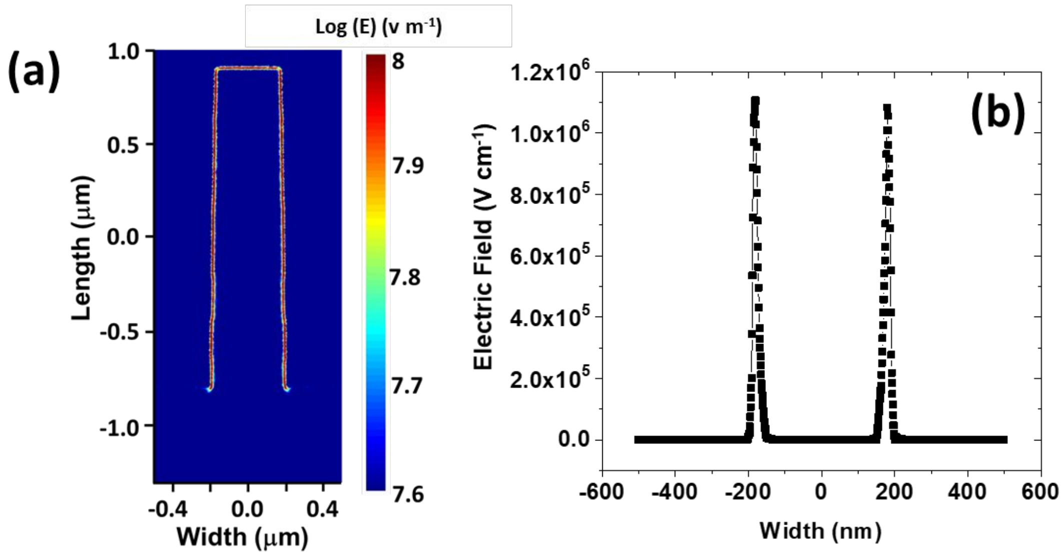


**Figure S2.** (a) Simulated electric field at the *n*-type AZO/ZnO and p-type InP at 0V, and (b) line plot of built-in electric field across the radial p-n junction.

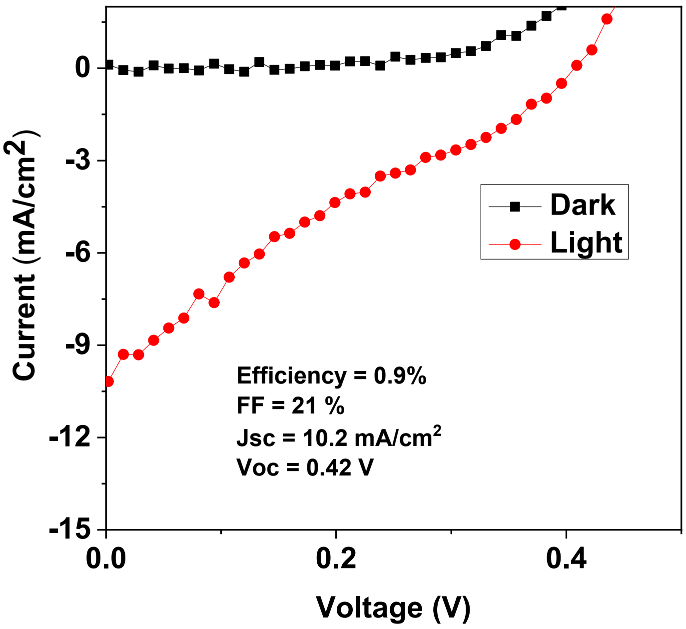


**Figure S3.** Dark and light IV characteristics of the reference planar solar cell.

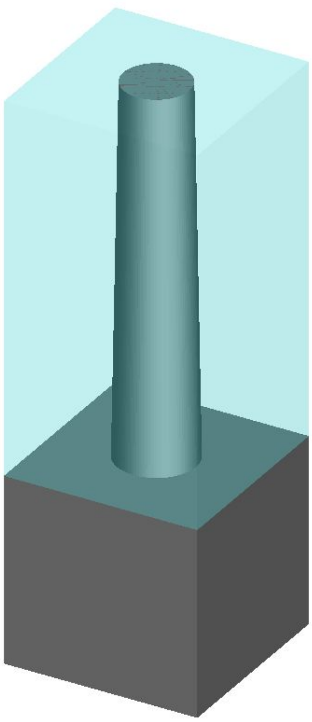

**Figure S4.** Geometric filling ratio is volume of cone (shown in grey) to the volume of cuboid (shown in light blue) base of which is equal to pitch of nanocone array and height of which is equal to the height of nanocones.

Geometric filling ratio is the ratio of the volume covered by the nanocone to the volume of a cuboid, base of which is equal to pitch of nanocone array and height of which is equal to the height of nanocones (see Figure S4). Therefore, the geometric filling ratio for a tapered nanowire (or nanocone) can be mathematically written as:

$$Filling\ Ratio\ (FR) = \frac{Volume\ of\ nanocone}{Volume\ of\ cuboid} = \ = \frac{1}{3}\pi \frac{R_{top}^2 + \ R_{top}\,.\,R_{base} + R_{base}^2}{Pitch^2}$$

**Double diode fitting**

The dark diode current under forward bias is only due to recombination. This recombination can occur within the depletion region, within the quasi-neutral regions, or at the metal-semiconductor Ohmic contacts. Dark IV of a solar cell under forward bias can give a lot of information related to recombination happening in the solar cell.[1]The dark IV characteristic of a *p-n* junction can be fitted almost accurately using a double diode equation given as:[1]

$$J = J_{01}\left[\exp\left(\frac{qV}{n_1 kT}\right) - 1\right] + J_{02}\left[\exp\left(\frac{qV}{n_2 kT}\right) - 1\right] \qquad \text{S (1)}$$

where, $J_{01}$ is the dark current contributions from ideal diode diffusion and $J_{02}$ is the dark current due to recombination happening in the depletion region, and $n_1$ and $n_2$, are the ideality factors of respective diodes. Furthermore, Wolf et.al have shown that the first part of the right hand of the equation is dominated at larger bias voltages (> 0.4 V), whereas, the second component in right hand of the equation at lower voltages.[2] In addition, a correction term can be introduced in above equation to account for series and shunt resistances as follows:

$$J = J_{01}\, exp\left[\frac{q(V - JR_s)}{kT}\right] + J_{02}\, exp\left[\frac{q(V - JR_s)}{n_2 kT}\right] + \frac{V - JR_s}{R_{Shunt}} \qquad \text{S (2)}$$

In equation S(2), -1 terms in the exponential of equation S1 is ignored as it makes the analysis easier and is a valid approximation. Both equations S (1) and S (2) can be used to extract the values of $J_{01}$ and $J_{02}$. $J_{01}$ and $J_{02}$ give a qualitative estimate of the recombination happening in the bulk/surface and in the depletion region, respectively.[2]

**Loss Calculations:**

The loss calculation performed in this paper is based on the work of Armin *et al*.[3] For loss calculation, a precise measurement of following physical parameters was necessary:

(1) 1-sun IV curve: To measure precise light IV of the proposed heterojunction solar cell, the solar simulator was calibrated to one-sun using a standard sample provided by the company, before every measurement. The one sun IV curve was used to evaluate the $V_{oc}$, $J_{sc}$, FF, and efficiency of the device.

(2) Dark IV: For precise dark IV measurement, the sample was covered with a thick aluminium foil and the lights were switched off before performing the measurements.

(3) Light series and shunt resistances were extracted by fitting the light IV curve using double diode equation.

(4) Shading fraction from the surface was calculate using following equation:

$$Shading\ fraction = \frac{M_{area}}{N_{area}} \times 100 \#S(3)$$

Where, $M_{area}$ denotes the faction of nanowire array covered with metal, and $N_{area}$ denotes total area of the nanowire array.

(5) External Quantum Efficiency (EQE), Internal quantum efficiency (IQE) and reflectance (R) was measured using a high precision EQE measurement setup from NewSpec. The EQE, IQE and R were measured for whole solar cell area (defined by total area covered with nanowire), as well for active area (i.e. the metal-free regions of the front surface).

**** Any spatial non-uniformity was ignored during the loss analysis.

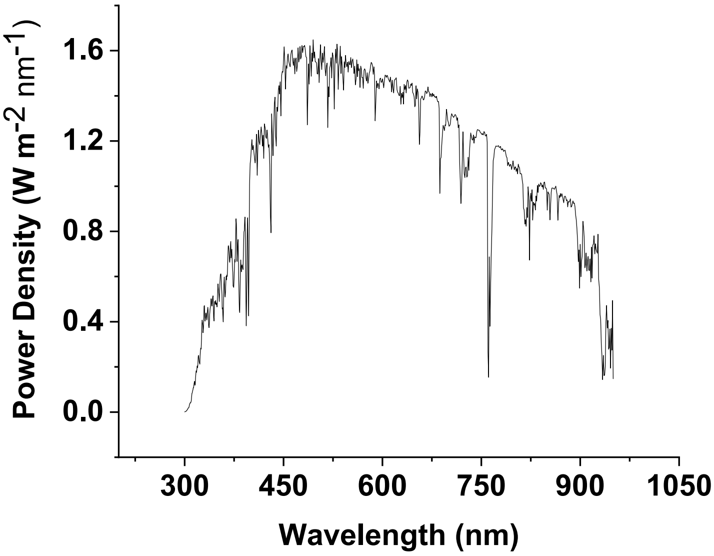


**Figure S3.** Solar power density profile used to calculation of $J_{sc}$ when quantum efficiency is 100% within 300-920 nm wavelength.

Equation used for loss analysis are:

$$Metal\ shading\ loss = shading\ fraction \times V_{mpp} \times J_{mpp} \#S(4)$$

$$J_{sc(EQE)} = \int_{\lambda 1}^{\lambda 2} \frac{q\lambda}{hc} \{EQE(\lambda).\ AM1.5G(\lambda)\}\ d\lambda \#S(5)$$

$$Series\ Resistance\ Loss = \ R_{s(light)} * J_{mpp}^2 \ \#S(6)$$

$$Shunt\ Resistance\ Loss = \frac{V_{shunt}^2}{R_{shunt}} \#S(7)$$

$$where,\ \ V_{shunt} = V_{mpp} + \ (R_{s(light)} * J_{mpp}^2) \#S(8)$$

The current loss at maximum power point can be written be written as:

$$Current\ Loss\ at\ MPP = (J_{sc} - J_{mpp} - J_{shunt}) \#S(9)$$

$$where,\ J_{shunt} = \frac{V_{shunt}}{R_{shunt}} \#S(10)$$

In the above equation, $J_{mpp}$ is the recombination current at maximum power point, whereas, $J_{shunt}$ is current loss due to shunt. Therefore, the current loss at maximum power point (MPP) is due to recombination in different regions of the solar cells at maximum power point. Though shunt losses also contribute to the current loss at MPP, in our case, shunt resistance is extremely high and current loss due to shunt is very little.

In addition, loss due to non-perfect IQE was calculates assuming that under ideal condition, IQE should 100% within 300-920 nm.

**Table S1.** Device parameters for five samples fabricated to test the reproducibility of the process. (Number given in bracket denote the active area values of a solar cell)

| Samples | $V_{OC}$ (Volts) | $J_{SC}$ (mA/cm$^2$) **(active area $J_{sc}$)** | Fill Factor (%) | Efficiency, η (%) **(active area η)** |
|---|---|---|---|---|
| **S1** | 0.736 | 29.54 **(31.3)** | 74.6 | 16.21**(17.2)** |
| **S2** | 0.694 | 29.48 **(31.2)** | 74.7 | 15.28**(16.2)** |
| **S3** | 0.687 | 28.97 **(30.7)** | 73.1 | 14.54 **(15.4)** |
| **S4** | 0.712 | 29.3 **(31.0)** | 71.3 | 14.87 **(16)** |
| **S5** | 0.699 | 29.25 **(31)** | 71.6 | 14.63**(15.5)** |
| ***Mean*** | ***0.71*** | ***29.30 (31.0)*** | ***73.06*** | ***15.1 (16.0)*** |

**References:**


1. Sah, C.; Noyce, R. N.; Shockley, W., Carrier Generation and Recombination in *p-n* Junctions *and p-n* Junction Characteristics. *Proc. IRE* **1957,** *45*, 1228-1243.
2. Wolf, M.; Noel, G. T.; Stirn, R. J., Investigation of the Double Exponential in the Current—Voltage Characteristics of Silicon Solar Cells. *IEEE Trans. Electron. Devices* **1977,** *24*, 419-428.
3. Aberle, A. G.; Zhang, W.; Hoex, B., Advanced Loss Analysis Method for Silicon Wafer Solar Cells. *Energy Procedia* **2011,** *8*, 244-249.