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1 **Triple Radial Junction Hydrogenated Amorphous Silicon Solar Cells with > 2 V**
2 **Open Circuit Voltage**

3

4 *Chaoqi Wang, Martin Foldyna, Erik V. Johnson, Pere Roca i Cabarrocas**

5

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- 1 Keywords: silicon nanowires, hydrogenated amorphous silicon, solar cells, triple
- 2 junction, high open circuit voltage
- 3

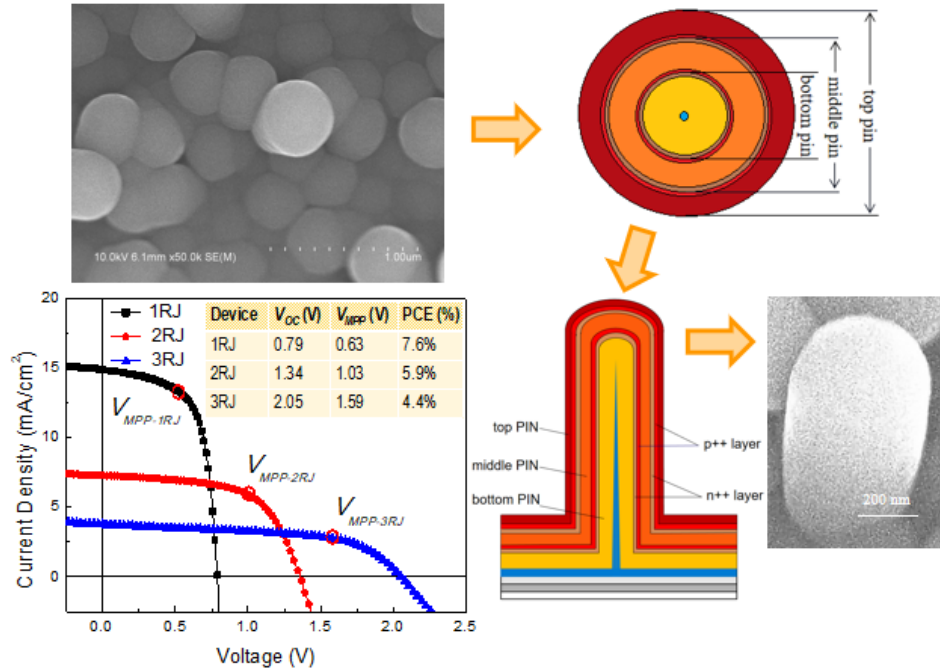
1 **Abstract:**

2 When solar cells are used as the photoanode for direct water splitting, the output
3 voltage required typically exceeds that of a single junction photovoltaic device.
4 Towards this application, in this work, triple radial junction silicon nanowire (3RJ
5 SiNW) solar cells are fabricated via a plasma-assisted vapor-liquid-solid method using
6 hydrogenated amorphous silicon (a-Si:H) for all the absorber layers, as well as for the
7 doped ones. A high open circuit voltage (V_{oc}) of 2.05 V, short circuit current density
8 (J_{sc}) of 3.8 mA/cm², and power conversion efficiency of 4.4% are obtained for solar
9 cells with areas of 0.03 cm² by optimizing the density of SiNWs grown on
10 ZnO:Al/Ag/Corning glass substrates. For lower efficiency devices, however, V_{oc}
11 values as high as 2.2 V are repeatedly achieved. At these higher voltages, large
12 variations in J_{sc} are observed, attributed to small local variations in SiNW density. This
13 work demonstrates for the first time, to our knowledge, the excellent potential of 3D
14 radial junction solar cells for applications requiring high voltages and high surface areas,
15 such as water splitting.

16

1 **Graphical Abstract:**

The First Radial a-Si:H/a-Si:H/a-Si:H Triple Junction Solar Cells



2

3 The a-Si:H based triple junction PIN solar cells are built on c-Si nanowires. They deliver 2.05 V
4 open circuit voltage, 3.8 mA/cm² current density, 0.57 fill factor, resulting in a 4.4% energy
5 conversion efficiency.

6

1 **Highlights:**

- 2 1. a-Si:H/a-Si:H/a-Si:H triple radial junction SiNW solar cells are fabricated.
- 3 2. SiNW solar cells with open circuit voltage over 2 V are achieved.
- 4 3. SiNWs can improve the contact between ZnO:Al substrate and PIN junction.

1 **1. Introduction**

2 There are many economically viable renewable energy sources available for
3 humankind, but a major challenge is storing the energy [1-4]. Hydrogen is currently
4 being explored as a clean energy vector, and producing hydrogen through water
5 splitting using photovoltaics (PV) is a solution consistent with a low carbon future.
6 Hydrogenated amorphous silicon (a-Si:H), used in a PIN structure, is a promising and
7 robust technology for PV solar cells in terms of silicon abundance, low cost, large areas,
8 and ability to operate in an aqueous environment [5-11]. By combining a-Si:H with
9 lower bandgap materials such as hydrogenated amorphous silicon-germanium or
10 microcrystalline silicon, double (tandem) and triple junction a-Si:H solar cells have
11 been investigated, which yield a higher efficiency due to better utilization of the solar
12 spectrum [12-16]. However, the disordered a-Si:H matrix limits photo-carrier collection
13 and Fermi-level splitting, and leads to conversion efficiencies limited to 12.34% in
14 stabilized 1.4 m² tandem micromorph (a-Si:H/ μ c-Si:H) modules and 16.3% initial
15 efficiency for triple junction devices [17, 18].

16 However, these structures were optimized for efficiency, and not for the specific
17 application of water splitting. Precisely, a minimum voltage of 1.23 V is required for
18 water splitting, according to thermodynamic calculations [19, 20]. Still, the reaction
19 will proceed infinitely slowly at this voltage, so an even higher voltage is required to
20 drive the reaction, with a greater voltage making the reaction happen faster. In addition
21 to this higher voltage requirement, a technology that is robust, stable, can be produced
22 over large surface areas, and provides a large specific surface area for the catalysis is
23 ideal for this application.

24 Silicon nanowire (SiNW) solar cells have emerged as an interesting alternative
25 architecture for thin film a-Si:H PV devices [21-24]. In this case, the PIN junction is
26 built on crystalline SiNWs, and forms a radial junction (RJ), which can enhance the
27 light trapping and absorption, allowing for thinner devices. Due to this, a strong built-
28 in electric field is present for better carrier separation and stability against light-induced
29 degradation [6].

30 Concerning the growth process and structure of SiNW solar cells, there are several

1 aspects that are ongoing research topics. Firstly, low melting point metal catalysts, such
2 as indium (In), gallium (Ga), bismuth (Bi) and tin (Sn), have been used for SiNW
3 growth in plasma-enhanced chemical vapor deposition (PECVD) [15-18, 25-30].
4 Recently, mixed metals applied as catalysts for SiNW growth have received increasing
5 attention; for instance, Bi-Sn alloys can provide an n-type doping of SiNWs without
6 the use of toxic dopant gases [24]. As well, a Cu-Sn bimetallic catalyst has been used
7 to grow SiNWs with a metastable hexagonal 2H crystalline structure [31]. Secondly,
8 the growth parameters (RF power, substrate temperature, deposition pressure and
9 doping gases) of SiNWs are also continually studied to further optimize the
10 performance of SiNW solar cells [5]. Finally, the use of low cost and flexible substrates
11 is another promising application for SiNWs. Indeed, single junction SiNW solar cells
12 grown on aluminum foil enable a high power-to-weight performance at low cost. A
13 power conversion efficiency of 5.6% has been recorded even at a bending radius of 5
14 mm [32].

15 Combining the RJ concept with a-Si:H multijunctions is another promising
16 research pathway. PIN-PIN tandem a-Si:H solar cells have already been demonstrated
17 in solar mini-modules. Due to their improved stability, they showed a higher end of life
18 aperture efficiency relative to single junction mini-modules [33, 34]. In addition,
19 because a-Si:H/a-Si:H tandem solar cells have lower current density than that of a-Si:H
20 single junction, they can also reduce the resistive losses in the case of a poor
21 conductivity of the transparent conductivity oxide (TCO) substrates [35]. Finally,
22 multijunction solar cells using the same bandgap for the absorber layer are being
23 explored for applications requiring higher voltages, such as for efficient solar to fuel
24 conversion [36].

25 In this work, triple radial junction (3RJ) SiNW solar cells are demonstrated, with
26 a particular focus on the optimization of the SiNW density to maximize operating
27 voltage. This is done with reference to the voltages needed to achieve water-splitting.
28 The performance of planar a-Si:H solar cells is also studied as a reference case and to
29 understand the limiting factors when optimizing 3RJ solar cells. The 3RJ SiNW solar
30 cells show unique merits as next generation high V_{oc} solar devices, in particular for

1 water splitting where the operating voltage should be significantly greater than 1.23 V.

2

1 **2. Experimental Description**

2 **2.1 Fabrication of SiNW radial junction solar cells**

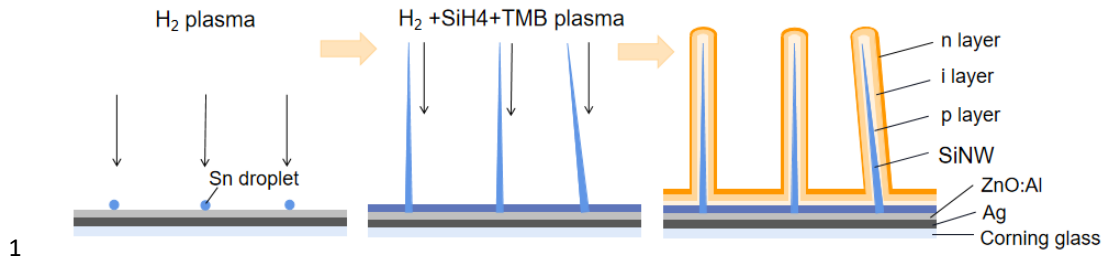
3 The first step of the growth of SiNWs is the formation of the catalyst drops (Sn in
4 this work) from which the VLS growth of NWs will occur. In previous works, Fluorine
5 doped SnO₂ (FTO) has been used for SiNW growth, with the Sn droplets formed by a
6 reducing H₂ plasma [37-39]. However, using this approach makes it difficult to control
7 the SiNW density. Therefore, in the current study, the Sn droplets were instead formed
8 from a thin evaporated layer of Sn on top of a 1 inch× 1 inch ZnO:Al/Ag/Corning glass
9 (CG) substrate stack. A 60 nm layer of Ag first was deposited on the CG by RF
10 magnetron sputtering (Alliance Concept) under a RF power of 50 W in 43 sccm Ar for
11 3 min. Then, 90 nm of ZnO:Al was sputtered with a RF power of 250 W in 30 sccm Ar
12 for 3 min, both at room temperature. The Sn catalyst was deposited on the
13 ZnO:Al/Ag/Cg stack by thermal evaporation in a bell jar chamber. The nominal
14 thicknesses of the Sn catalyst layers are 0.02 nm, 0.08 nm, 0.1 nm, 0.2 nm and 0.8 nm.

1 The substrates were then loaded into the PECVD chamber. The PECVD tool
2 used in this work is a capacitively-coupled reactor. The top, shower-head electrode is
3 the powered electrode, driven at a frequency of 13.56 MHz, and the bottom, substrate
4 holder electrode is grounded. Both electrodes are heated, and a grounded plasma box is
5 present, surrounding both electrodes. The base pressure of the reactor is below $5 \times$
6 10^{-5} mbar and the working pressure is in the range of 0.1 to 2 mbar. Once base
7 pressure is achieved, the substrates were exposed to a H₂ plasma at 250 °C for 2 min in
8 order to reduce the oxide layer formed on top of the evaporated Sn, and obtain Sn
9 droplets. The different thicknesses of Sn give different droplet densities to then be used
10 as catalysts for plasma-assisted vapor-liquid-solid (VLS) growth of SiNWs. The H₂
11 flow rate, RF power density and chamber pressure were 100 sccm, 5 W and 1.8 mbar,
12 respectively. Afterwards, while the temperature of the substrate holder was increased to
13 600 °C, 10 sccm SiH₄, 100 sccm H₂ and 1.5 sccm trimethylboron (1% TMB diluted in
14 H₂) were flowed into chamber. When the substrate reached the nominal temperature of
15 600 °C, SiNWs were grown for 10 min by igniting a plasma at an RF power of 2 W and
16 a pressure of 1.38 mbar (see Figure 1). After that, the chamber was cooled down to 220 °C
17 under an H₂ atmosphere, to be followed by p-type, intrinsic and n-type a-Si:H layer
18 growth by PECVD.

19

20 All deposition conditions for single (1RJ), double (2RJ), and triple (3RJ) radial
21 junctions are given in Table 1. For the 1RJ growth, a p-type a-Si:H layer with a dopant
22 gradient was first deposited on SiNWs (Table 1). After the graded p-layer growth, the
23 undoped, i-a-Si:H layer was immediately deposited by closing the TMB flow and
24 allowing growth to continue for 45 min. Then, a graded n-type a-Si:H layer was
25 deposited on the intrinsic a-Si:H layer. This process is depicted in Figure 1.

26



1

2

Figure 1. Schematic of the fabrication process of SiNW radial junction solar cells:

3

a) Sn catalyst formation via H₂ plasma treatment; b) p-type SiNWs growth in a

4

mixture of SiH₄, H₂ and TMB; c) The complete pin radial junction solar cell.

1

Table 1. Parameters for growing SiNW solar cells

Cell	Material	SiH ₄ Flow [sccm]	Doping Gas	Doping Gas Flow [sccm]	RF Power [W]	Pressure [mbar]	Time (1J) [min]	Time (2J) [min]	Time (3J) [min]
Bottom	p-a-Si:H	10	1% TMB:H ₂	3/2/1	2	0.18	3/1/1	3/1/1	3/1/1
	i-a-Si:H	10	-	-	2	0.16	45	45	32
	n-a-Si:H	10	1% PH ₃ :H ₂	1/2/7	1	0.38	0.7/0.7/2	0.7/0.7/2	0.7/0.7/2
Tunnel	n++ a-Si:H	4	1% PH ₃ :H ₂	10	1	0.28	-	2	2
Junctions	p++ a-Si:H	4	1% TMB:H ₂	10	1	0.28	-	2	2
Middle	p-a-Si:H	10	1% TMB:H ₂	5	1	0.18	-	-	5
	i-a-Si:H	10	-	-	2	0.16	-	-	16
	n-a-Si:H	10	1% PH ₃ :H ₂	1/2/7	1	0.38	-	-	0.7/0.7/2
Top	p-a-Si:H	10	1% TMB:H ₂	5	1	0.18	-	5	5
	i-a-Si:H	10	-	-	2	0.16	-	20	8
	n-a-Si:H	10	1% PH ₃ :H ₂	1/2/7	1	0.38	-	0.7/0.7/2	0.7/0.7/2

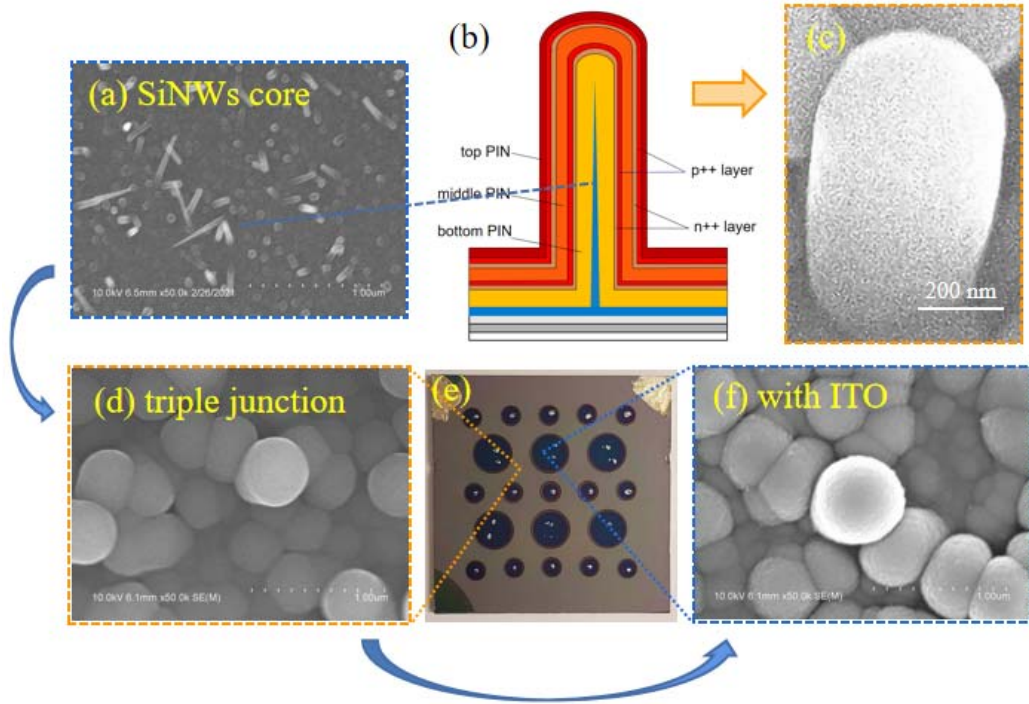
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1 For the 2RJ solar cells, after growing the first junction, highly doped n⁺⁺ and p⁺⁺
2 layers were deposited to form a tunnel recombination junction. The conductivities of
3 the n⁺⁺ a-Si:H and p⁺⁺ a-Si:H materials are $\sim 1 \times 10^{-2}$ S/cm and $\sim 3 \times 10^{-5}$ S/cm,
4 respectively.

5 For the next junction, a p-layer with a constant flow rate of 5 sccm TMB was
6 deposited, and the i-layer and n-layer were deposited as described before (see Table 1).

7 For the 3RJ solar cells, another n⁺⁺/p⁺⁺ junction was deposited after the middle
8 cell. The deposition conditions for the p, i, and n layers were identical to the middle
9 cell, except for the i-layer deposition times (see Table 1). Various steps of the fabrication
10 of 3RJ cells are represented in Figure 2. The side view and top view SEM images of
11 the triple junction are shown in Figure 2 (c) and (d). The final diameter of the triple
12 junction in Figure 2 (d) is around 500 nm. The deposition rate of the intrinsic layer on
13 flat glass substrate was determined to be 0.67 Å/s.

14 After PECVD, transparent Indium Tin Oxide (ITO) top contact pads were
15 sputtered on the solar cells through a shadow mask. The Ar and O₂ flow rates were 43
16 and 3 sccm, respectively, using a RF power of 200 W for 7 min at 4.4×10^{-3} mbar and
17 180°C. The SiNW solar cells were annealed in air at 240°C for 20 min after ITO
18 sputtering. Small Ag dots are placed on top of ITO pads for a better electrical contact
19 between the ITO and the probe. In Figure 2 (e), the picture shows a 1"×1" sample
20 containing 6 cells of 4 mm diameter (0.13 cm²) and 15 cells of 2 mm diameter (0.03
21 cm²) with ITO top contact. Figure 2(f) shows a SEM image of the triple junction with
22 ITO top contact. The diameter of triple junction with ITO pads in Figure 2(f) is around
23 600 nm.



1

2 **Figure 2.** Scanning electron image of SiNW core a) and schematic illustration of
 3 the 3RJ solar cell b), triple junction stack around one NW c), triple junction stack
 4 of and ensemble of 3RJs without ITO d) photograph of 1" x1" substrate e), 3RJ
 5 cells with ITO top contact f).

6

7 Planar a-Si:H solar cells were prepared using the same process steps on FTO
 8 substrates (MSE Supplies), but without the evaporation of the Sn catalyst nor the p type
 9 SiNWs growth.

10

11 2.2 Characterization

12 The current density-voltage (J-V) characteristics of the $\sim 0.03 \text{ cm}^2$ solar cells were
 13 measured at room temperature under standard AM1.5G illumination conditions with a
 14 power density of 100 mW/cm^2 (Solar Simulator, Newport). These measurements were
 15 performed in-house, and were not verified at a third-party measurement laboratory. As
 16 mentioned above, before measuring the solar cells, small contacts made from Ag paste
 17 were placed by hand on the top of ITO contacts (as shown in Figure 2 e). Due to the
 18 manual placement of these contacts, accidental partial shading by the probe, and the

1 fact that no shadow mask was used during measurement, the J_{SC} of the solar cells can
2 vary. The absolute measured values of J_{SC} have not been confirmed by EQE and should
3 be considered as approximate ($\pm 10\%$). The morphology of solar cells was characterized
4 by scanning electron microscopy (SEM, HITACHI S-4800). The silicon nanowire
5 density was calculated by counting the radial junctions visible in SEM without ITO top
6 contact, as demonstrated in the supplementary material (SI 1).

7

8

1 **3. Results and Discussion**

2 **3.1 Optimizing SiNW density for triple junction devices**

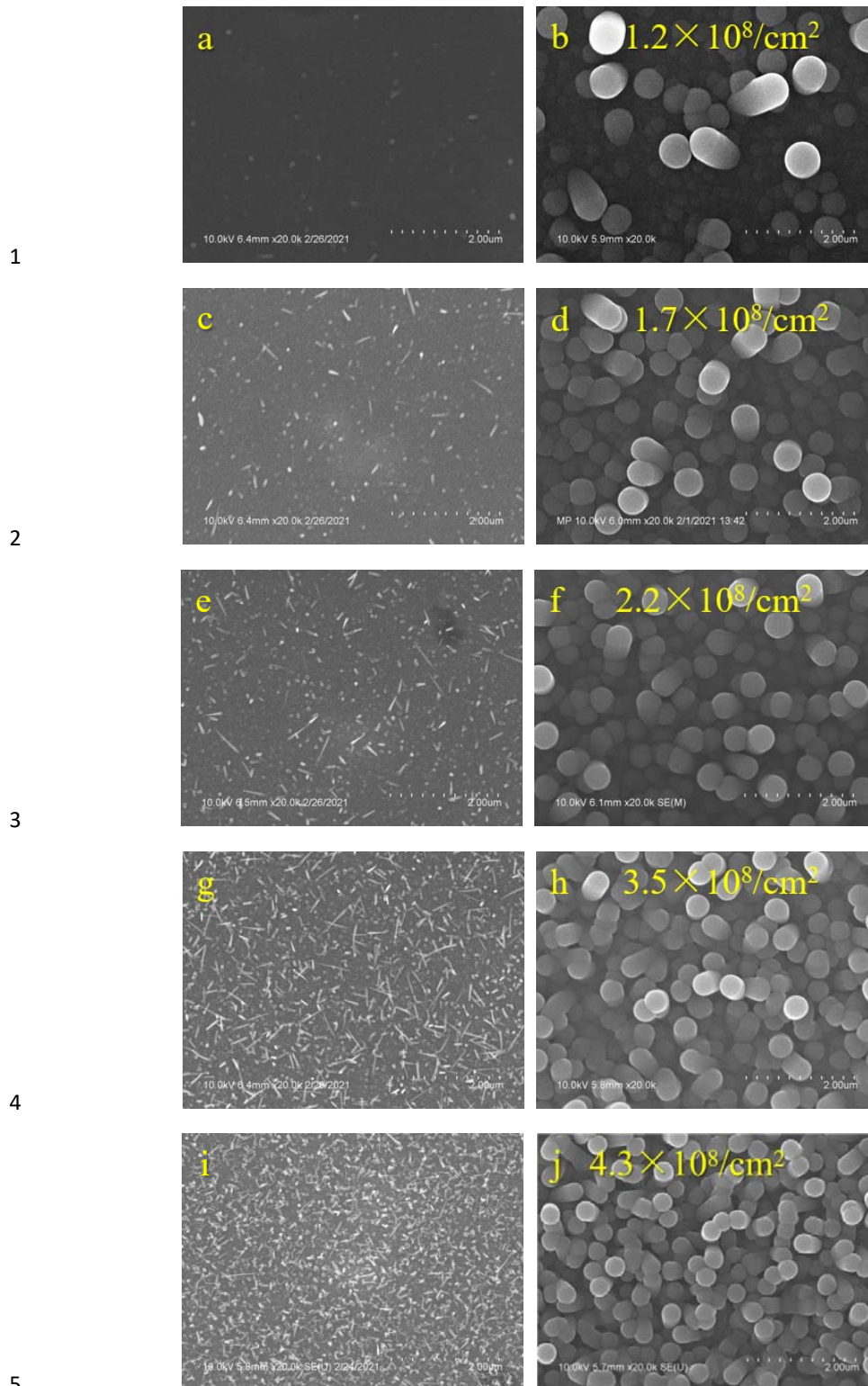
3 As shown in the work of S. Misra, there is an optimum in the density of single
4 radial junction solar cells of $\sim 2.6 \times 10^8/\text{cm}^2$ [6]. In that work, it was shown that starting
5 from a planar structure, short circuit current (I_{SC}) increases with NW density due to light
6 trapping, but the reverse dark saturation current (I_0) also increases due to the greater
7 effective surface area. One notes that there are 100's of millions of NWs per square
8 centimeter in such devices, so the increase in effective surface area can be dramatic.
9 The optimum occurs due to the tradeoff between I_{SC} and open circuit voltage (V_{OC}), as
10 approximated by $V_{OC} = kT \ln(I_{SC}/I_0)$. At yet higher densities, non-uniform radial
11 deposition along the length of the SiNW was also observed, which may play a role too.
12 For 3RJ SiNW solar cells, the total thickness of the stack is obviously greater than that
13 of the single junction. Therefore, the optimum density of SiNWs remains to be
14 determined for 3RJ solar cells.

15 In Figure 3, SEM images of the SiNW and complete 3RJ a-Si:H solar cells
16 (without ITO top contact) are presented. The density of silicon nanowire solar cells was
17 calculated by counting the radial junctions without sputtered ITO top contact, as shown
18 in the right row of images in Figure 3 (and as demonstrated in supplementary materials
19 S11). The densities are $1.2 \times 10^8/\text{cm}^2$, $1.7 \times 10^8/\text{cm}^2$, $2.2 \times 10^8/\text{cm}^2$, $3.5 \times 10^8/\text{cm}^2$ and
20 $4.3 \times 10^8/\text{cm}^2$. From Figure 3 one can see that the diameter of the silicon nanowire solar
21 cells decreases as their density increases [6-8, 23]. This is expected because the flux of
22 reactive species supplied by the plasma is constant while the total surface of the radial
23 junctions increases with SiNW density.

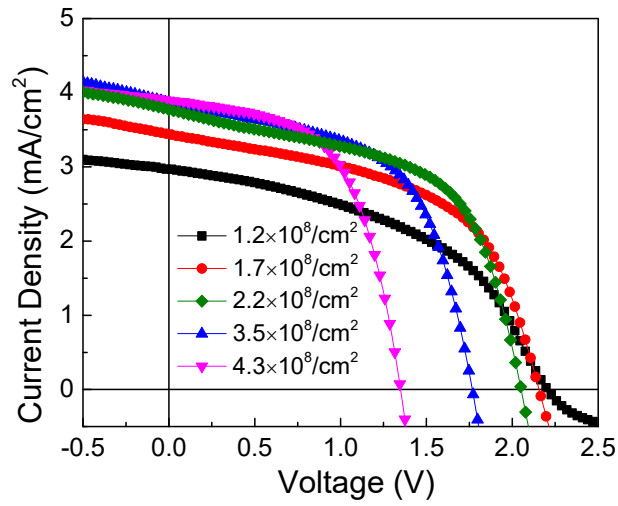
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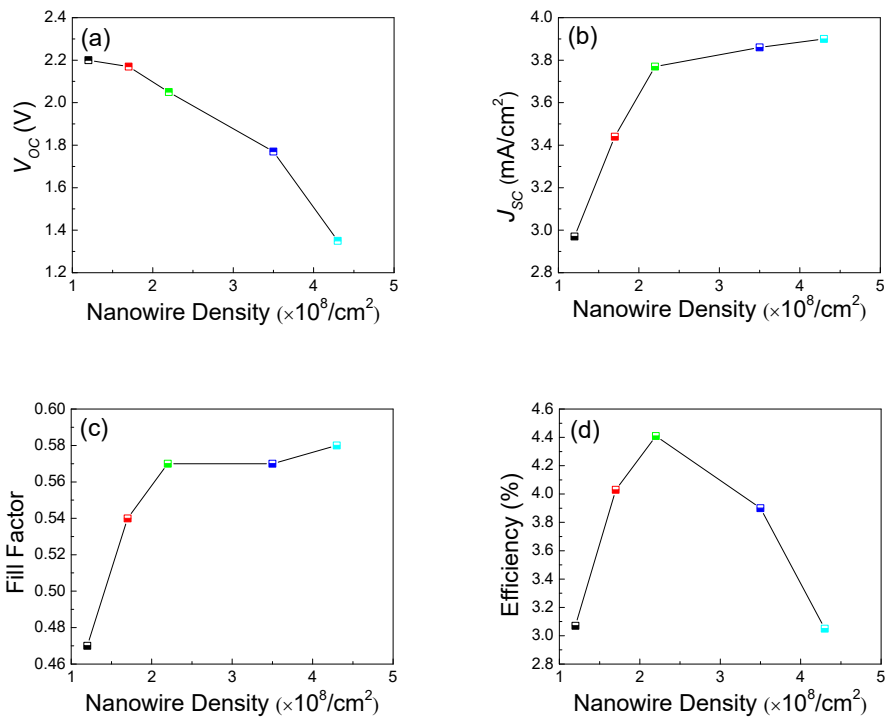
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 6 **Figure 3.** SEM images of SiNWs and 3RJ solar cells. Left row: SiNWs after VLS
 7 growth Right row: 3RJ solar cells with densities ranging from $1.2 \times 10^8/\text{cm}^2$ to
 8 $4.3 \times 10^8/\text{cm}^2$.



1
 2 **Figure 4.** J-V characteristics of 3RJ solar cells with different SiNW densities ranging
 3 from $1.2 \times 10^8/\text{cm}^2$ to $4.3 \times 10^8/\text{cm}^2$.



4
 5
 6 **Figure 5.** (a)-(d) The open circuit voltage (V_{oc}), the short current density (J_{sc}), fill
 7 factor (FF) and power conversion efficiency (η) of a-Si:H 3RJ solar cells as functions
 8 of SiNW density.

1 The J(V) characteristics of 3RJ solar cells with different densities are presented in
2 Figure 4. The open circuit voltage (V_{OC}), short circuit current density (J_{SC}), fill factor
3 (FF) and conversion efficiency (η) of the best 3RJ solar cells are plotted as functions of
4 SiNW densities in Figure 5(a)-(d), respectively.

5 As expected, Figure 5 (a) shows that V_{OC} decreases as the density of SiNWs
6 increases. At low SiNW density of $1.2 \times 10^8/\text{cm}^2$, a V_{OC} of 2.2 V is obtained but V_{OC}
7 drops to 1.35 V for a density of $4.3 \times 10^8/\text{cm}^2$. As discussed at the start of this section, a
8 higher density of NWs increases the effective surface area of the devices. This increases
9 the dark saturation current, I_0 , compared to a planar device. Once this effect is not fully
10 compensated by the increased short circuit current density, I_{SC} , this will lead to a
11 decreased V_{OC} ($V_{OC} = kT \ln(I_{SC}/I_0)$) [40-43]. Indeed, light trapping is more efficient with
12 increased SiNW density [6, 44, 45]. Figure 5 (b) shows a step increase in J_{SC} , but it
13 flattens out for SiNW densities above $2.2 \times 10^8 \text{ cm}^{-2}$ reaching a maximum of $3.9 \text{ mA}/\text{cm}^2$
14 for a density of $4.3 \times 10^8/\text{cm}^2$. Surprisingly, Figure 5(c) shows that the fill factor of 3RJ
15 solar cells increases quickly with SiNW densities from $1.2 \times 10^8/\text{cm}^2$ to $2.2 \times 10^8/\text{cm}^2$.
16 Afterwards, the FF has a slow increase from SiNW density of $2.2 \times 10^8/\text{cm}^2$ to
17 $4.3 \times 10^8/\text{cm}^2$. This is due to poor electrical contact between the absorber layers and the
18 planar areas between NWs, which increases in importance at low NW density. The
19 devices with the lowest density of SiNWs ($1.2 \times 10^8/\text{cm}^2$) display an "S-curve", with a
20 change of inflection around V_{OC} . This behavior is addressed in more detail in SI 2 and
21 3.

22 The calculated efficiency of 3RJ solar cells as a function of SiNW density is shown
23 in Figure 5(d), with a clear maximum at $2.2 \times 10^8/\text{cm}^2$ giving the best efficiency of
24 4.44%. At this point, the J_{SC} has increased to a higher value, but V_{OC} has not yet begun
25 to dramatically decrease.

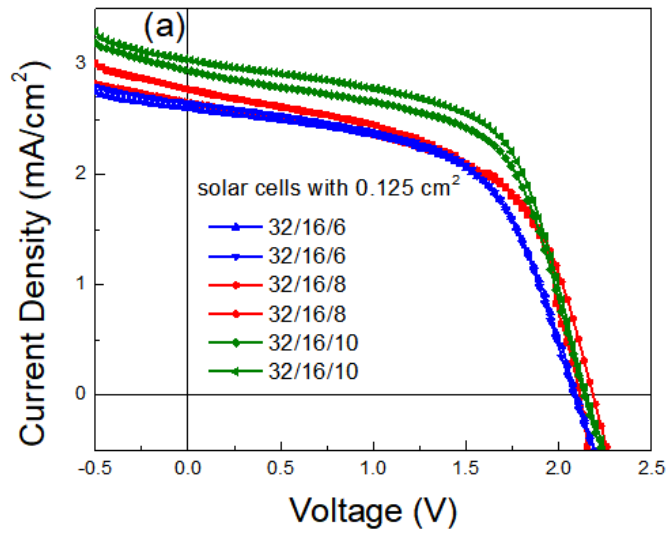
26 As expected, the SiNW density corresponding to the best performance is different
27 in single and triple junction. The best density value decreases from $2.6 \times 10^8/\text{cm}^2$ in the
28 case of the SJ [6] to $2.2 \times 10^8/\text{cm}^2$ in the case of the 3RJ. For 3RJ silicon nanowire solar
29 cells, the optimum density is expected to be lower because they have a larger diameter
30 than SJ.

1

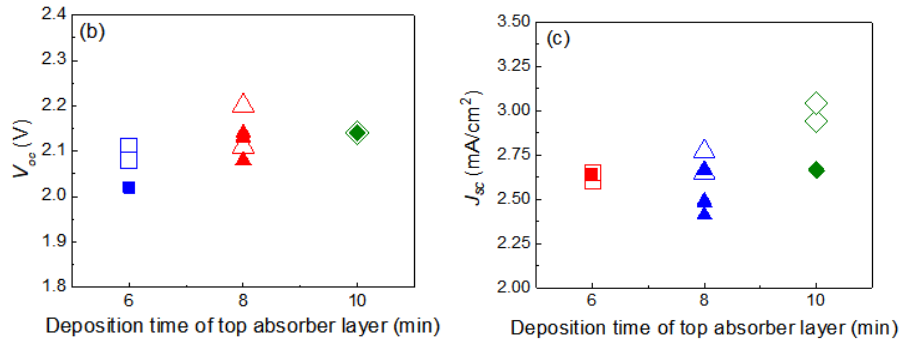
2 **3.2 Top layer thickness and SiNW density effect in high V_{oc} , 3RJ devices**

3 For the devices shown above, a first choice was made that the ratios of the layer
4 thicknesses in the 3J should go as 1:2:4 to approach current matching conditions.
5 However, this choice vastly oversimplifies the optimized choice of layer thicknesses
6 for 3RJ solar cells. To nevertheless analyze the dependence of the device behavior on
7 this ratio, a set of samples have been fabricated, varying the thicknesses of the top layers.
8 As already seen in Figure 5 above, the PV parameters achieved depend very strongly
9 on the value of NW density, particularly around the local efficiency optimum.
10 Therefore, we have chosen devices with similar, elevated values of V_{oc} (2.11 to 2.2 V),
11 as a proxy for local NW density, as this parameter is the hardest to control in this
12 technology.

13 Two representative J(V) curves of devices with areas of 0.125 cm² from each
14 substrate are presented in Figure 6(a). Furthermore, the statistical spread of V_{oc} and J_{sc}
15 for all working 0.125 cm² cells on each substrate are presented in Figures 6(b) and 6(c).
16



1



2

3 **Figure 6.** (a) J-V curves for SiNW 3RJ solar cells for three different deposition
 4 times (thicknesses) of the top cell. (b) V_{OC} and (c) J_{SC} values of all working cells on
 5 substrate, with cells of (a) highlighted as larger, open symbols.

6

7 The J-V curves of Figure 6(a) highlight two important facts: firstly, the elevated V_{OC}
 8 underlined in this work (targeted towards applications such as water splitting) is shown
 9 to be quite robust to variations in top layer thickness. Values above 2V are consistently
 10 produced. Secondly, the increasing thickness of the top i-layer seems to increase the
 11 overall J_{SC} (and the overall performance, as seen in Figure 6a). As the J_{SC} in such
 12 structures is determined by the current-limiting cell [46-48], this indicates that the top-
 13 cell is limiting in the present design. One should also note that the ratio of deposition
 14 times should not be interpreted as a thickness ratio, as it would be for planar devices.
 15 Due to the RJ architecture, under constant plasma conditions, deposition rate will

1 decrease with time as the SiNW increases in diameter and develops a larger surface
2 area. Furthermore, the spread in values of J_{SC} on a single substrate (Figure 6c) shows
3 difficulty of optimizing such high V_{OC} devices. As one can infer from Figure 5, when
4 targeting high V_{OC} values, one must use lower densities of NWs ($< 2 \times 10^8/\text{cm}^2$), and in
5 this range of densities, the short circuit current density is very sensitive to NW density.
6 In addition, process variations due to ZnO scattering, NW length, ITO contacts, and Ag
7 spot placement will impact J_{SC} , while V_{OC} remains quite stable.

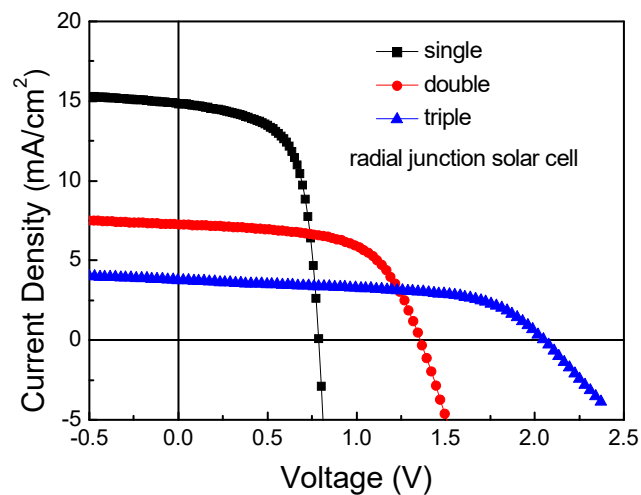
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9 4. Discussion

10 4.1 Comparing performance of 1J, 2J, 3J solar cells

11 It is interesting to directly compare the performance of single, double, and triple
12 junction devices made from a single absorber layer material. The J-V characteristics of
13 1RJ, 2RJ, and 3RJ solar cells are shown in Figure 7, and the associated PV parameters
14 are given in Table 2.

15



16

17 **Figure 7.** J-V characteristics of radial junction silicon nanowire solar cells with
18 single, double and triple junction.

19

20 As shown in Table 1, the V_{OC} values of the 1RJ, 2RJ, and 3RJ SiNW solar cells
21 are 0.79 V, 1.34 V and 2.05 V, respectively. According to the single diode model

1 describing a solar cell, one can use the formula $V_{OC} = nkT \ln(J_{SC}/J_0)$ to describe the
 2 tendency of V_{OC} as a function of illumination (approximated by J_{SC}). All else remaining
 3 equal, if the current density becomes lower, the V_{OC} will also decrease. For example,
 4 using this calculation, the expected V_{OC} for a double junction based on a single junction
 5 with 0.79V would be between 1.54 and 1.51V depending on the value of n , ignoring
 6 voltage losses in the tunnel junction [49]. For a triple junction, the expected values
 7 would be between 2.11V and 2.28V, so in fact, the voltage in the triple junction is very
 8 close to the maximum achievable value if we assume constant values of J_0 for both
 9 devices.

10 The J_{SC} values compared to the expected maximum are not as impressive for the
 11 triple junction. The 14.8 mA/cm² of the single junction could be divided between two
 12 junctions giving 7.4 mA/cm² each (actually 7.1 mA/cm²) or three junctions, giving 4.9
 13 mA/cm² (actually 3.8 mA/cm²). For the triple junction, some optical management is
 14 obviously still necessary to improve absolute efficiency, such as optimizing all layer
 15 thicknesses and using n-type hydrogenated microcrystalline silicon oxide ($\mu\text{-SiO}_x\text{:H}$)
 16 as the top-most doped layer [50].

17

18 **Table 2.** V_{OC} , J_{SC} , FF and power conversion efficiency (PCE) of single, double
 19 and triple junction SiNW solar cells.

Device	V_{OC} (V)	V_{MPP} (V)	J_{SC} (mA/cm ²)	FF	PCE (%)
1RJ	0.79	0.63	14.8	0.65	7.6%
2RJ	1.34	1.03	7.1	0.62	5.9%
3RJ	2.05	1.59	3.8	0.57	4.4%

20

21 One last point to note in Table 1 is that for the triple junction SiNW solar cells, the
 22 voltage at maximum power (V_{MPP}) is sufficiently high to drive unassisted water splitting;
 23 1.23 V is the minimum voltage required for water splitting, plus an overvoltage to
 24 increase the rate, depending on the catalysts used [19, 20]. This underlines the interest
 25 in such devices for this application, as such 3RJ devices can directly supply such a
 26 voltage.

1

2 **5. Conclusion**

3 With the goal of an elevated operating voltage suitable for water splitting, an a-
4 Si:H based silicon nanowire triple radial junction (SiNW 3RJ) solar cell has been
5 successfully fabricated using a one-pump-down plasma-assisted VLS method. The
6 SiNW solar cell is grown by using a combination of ZnO:Al and evaporated Sn as a
7 substrate and catalyst. The SiNW 3RJ solar cell performance depends strongly on
8 nanowire density. When optimizing for efficiency, a nanowire density of $2.2 \times 10^8/\text{cm}^2$
9 leads to a V_{oc} up to 2.05 V, J_{sc} of 3.8 mA/cm², FF of 0.57 and an efficiency of 4.4%.
10 Higher values of V_{oc} up to 2.2 V are achieved, but at the cost of a greater variability in
11 J_{sc} due to the random nature of SiNW growth.

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3

1 **Supporting Information**

2 Supporting Information is available from the Wiley Online Library or from
3 the author.

4

1 **Conflict of Interest**

2 The authors declare no conflict of interest.

3

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