Supporting Information

Dual-Functional Carbon-Doped Polysilicon Films for Passivating Contact Solar Cells: Regulating Physical Contacts while Promoting Photoelectrical Properties

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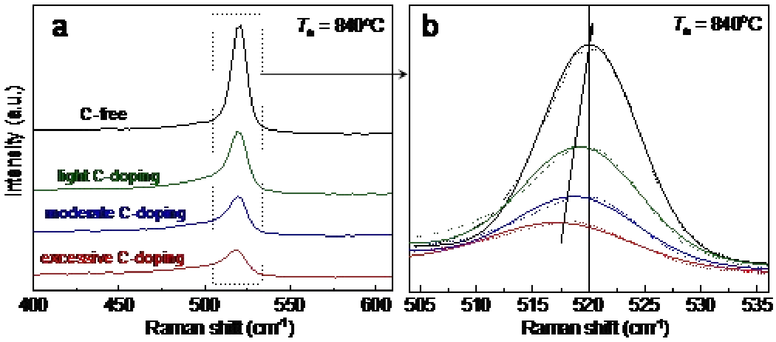


Figure S1. Raman spectra under the different Raman shift ranges at T_a = 840°C.

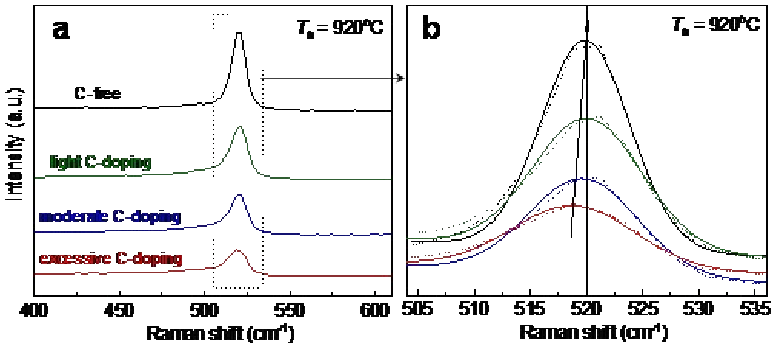


Figure S2. Raman spectra under the different Raman shift ranges at T_a = 920°C.

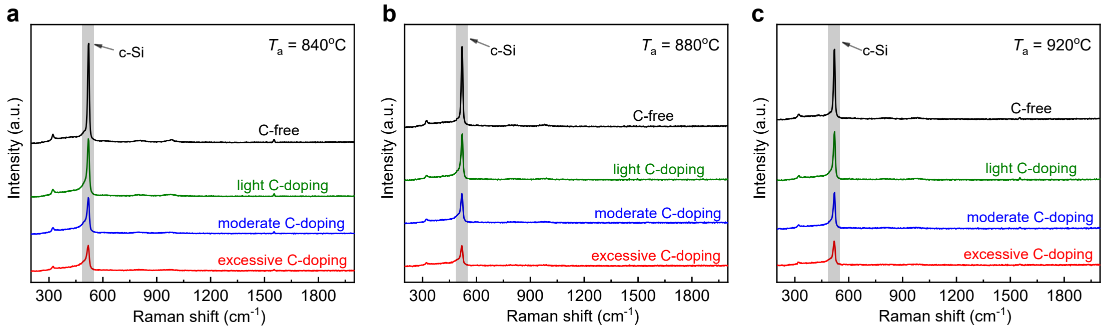


Figure S3. Full Raman spectra for the four related samples at T_a = (a) 840°C, (b) 880°C and (c) 920°C.

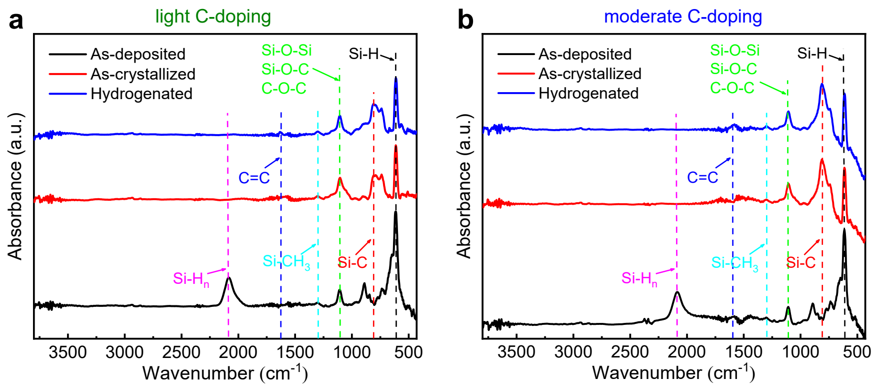


Figure S4. FTIR spectra for the (a) lightly and (b) moderately C-doped samples.

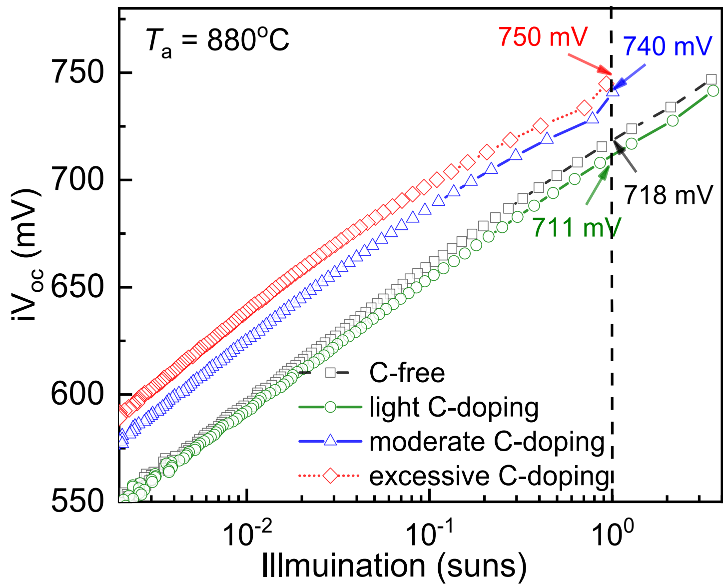


Figure S5. Suns-iV_{oc} for the four related samples at T_a = 880°C.

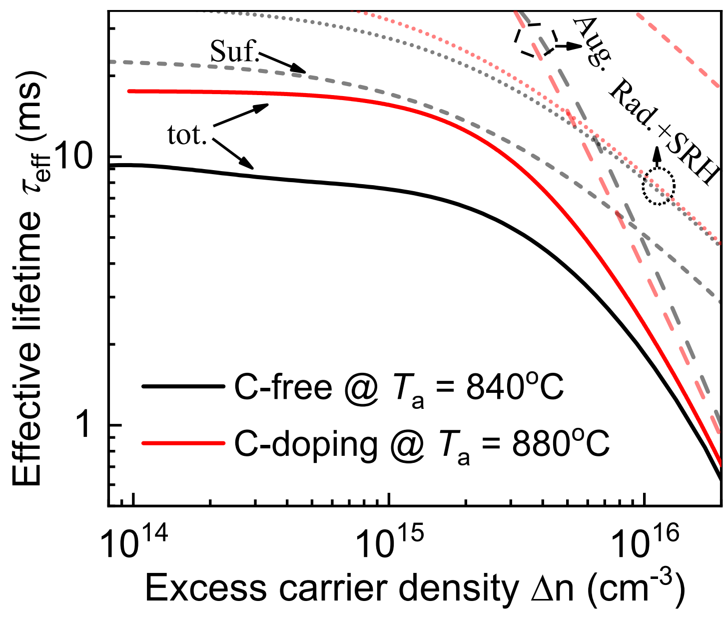


Figure S6. Fitted τ_{eff} as a function of Δn.

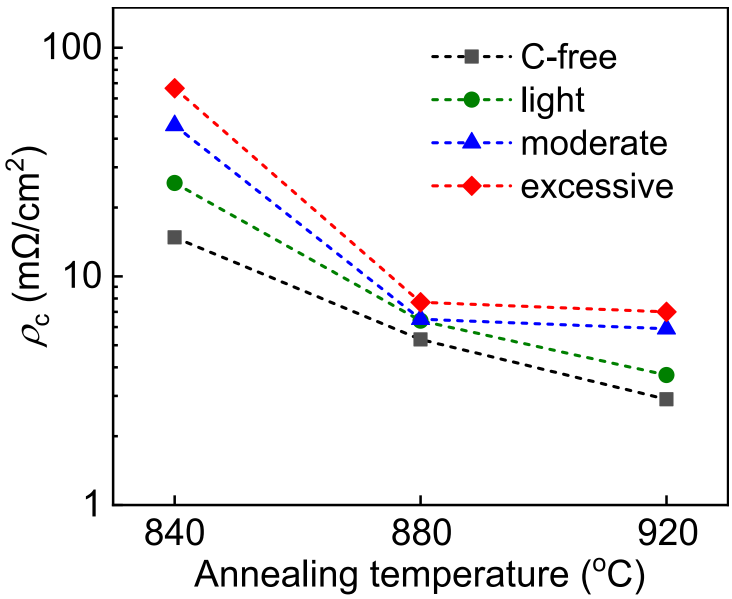


Figure S7. ρ_c as a function of Ta for the C-free and lightly, moderately and excessively C-doped samples.

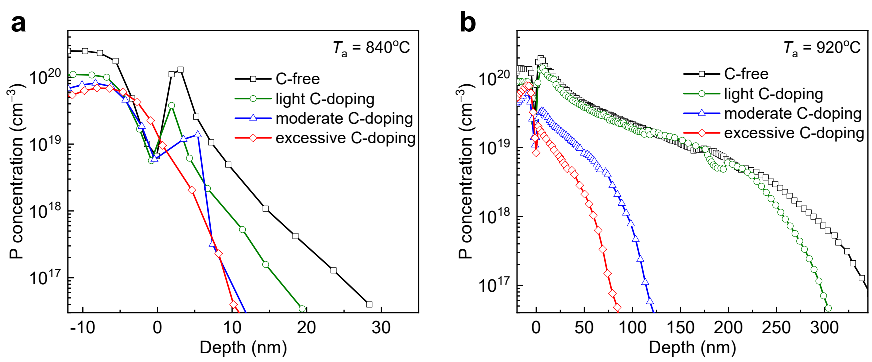
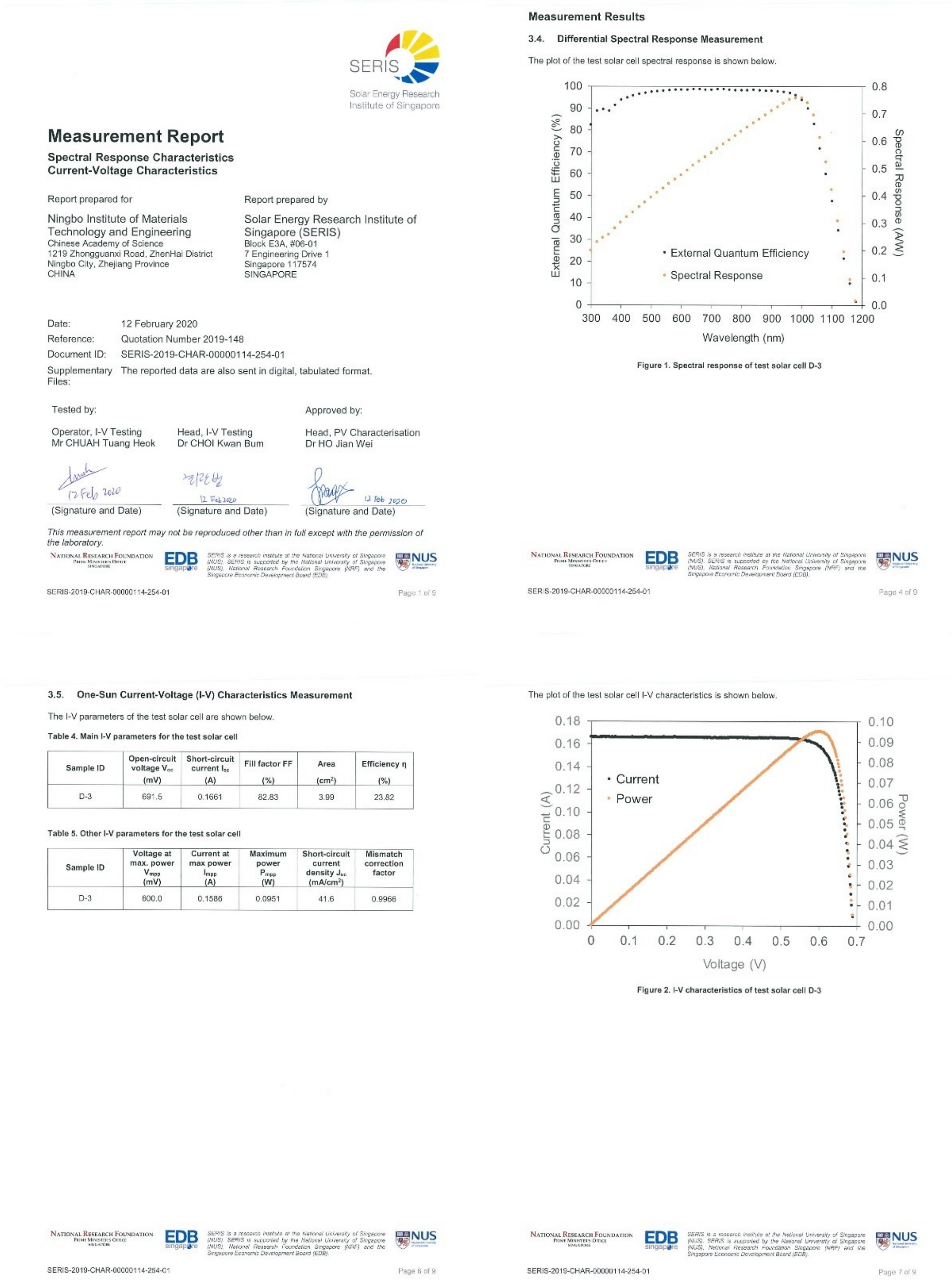


Figure S8. Profiles of active P concentration measured by ECV for the four related samples at T_a = (a) 840°C and (b) 920°C.



SERIS
Solar Energy Research Institute of Singapore

Measurement Report

Spectral Response Characteristics
Current-Voltage Characteristics

Report prepared for

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Tested by:

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Measurement Results

3.4. Differential Spectral Response Measurement

The plot of the test solar cell spectral response is shown below.

Figure 1. Spectral response of test solar cell D-3

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3.5. One-Sun Current-Voltage (I-V) Characteristics Measurement

The I-V parameters of the test solar cell are shown below.

Table 4. Main I-V parameters for the test solar cell

Sample ID	Open-circuit voltage V_{oc} (mV)	Short-circuit current I_{sc} (A)	Fill factor FF (%)	Area (cm²)	Efficiency η (%)
D-3	691.5	0.1661	82.83	3.99	23.82

Table 5. Other I-V parameters for the test solar cell

Sample ID	Voltage at max. power V_{mpp} (mV)	Current at max power I_{mpp} (A)	Maximum power P_{mpp} (W)	Short-circuit current density J_{sc} (mA/cm²)	Mismatch correction factor
D-3	600.0	0.1586	0.0951	41.6	0.9966

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The plot of the test solar cell I-V characteristics is shown below.

Figure 2. I-V characteristics of test solar cell D-3

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Figure S9. Device certified report by SERIS.

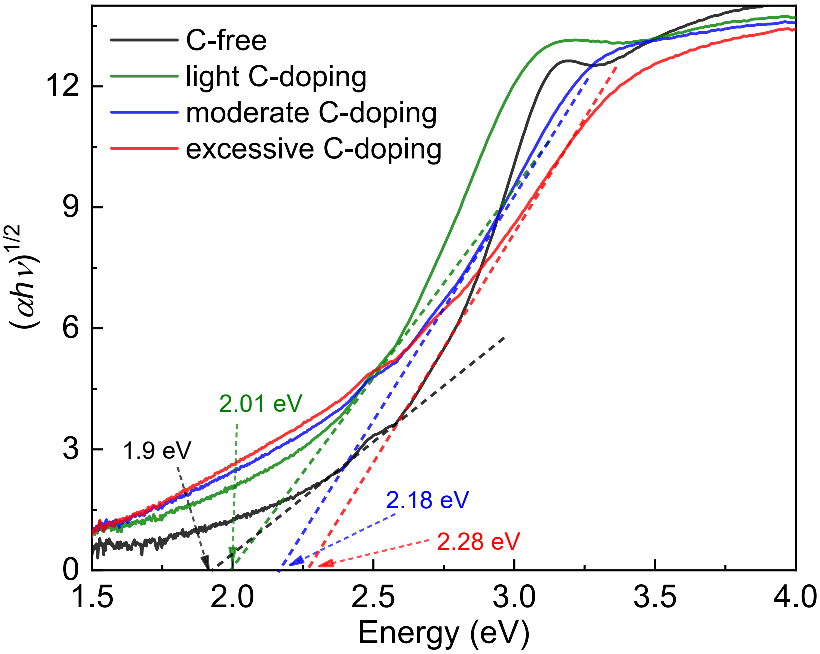

Figure S10. Plots of $(\alpha h\nu)^{1/2}$ vs energy for the four related samples.

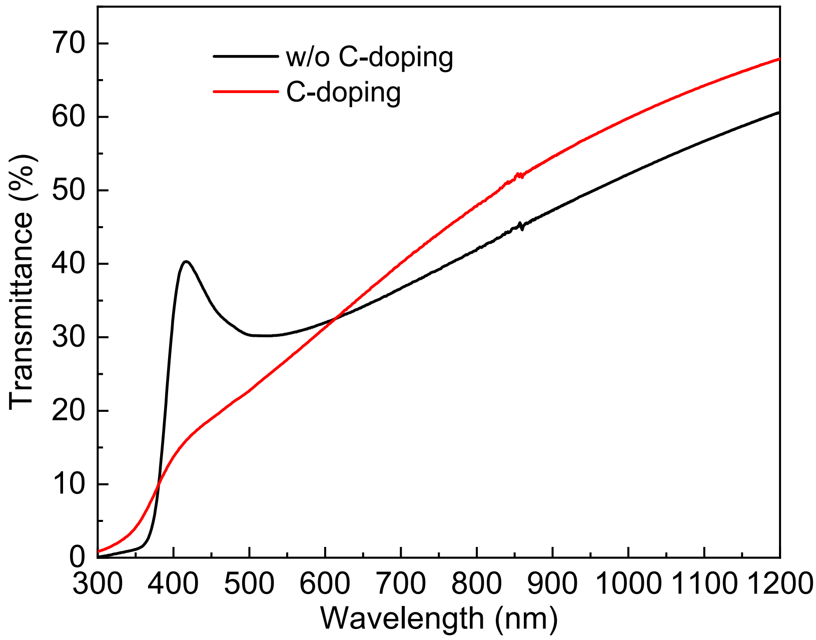

Figure S11. Transmission spectra of the two related cases.

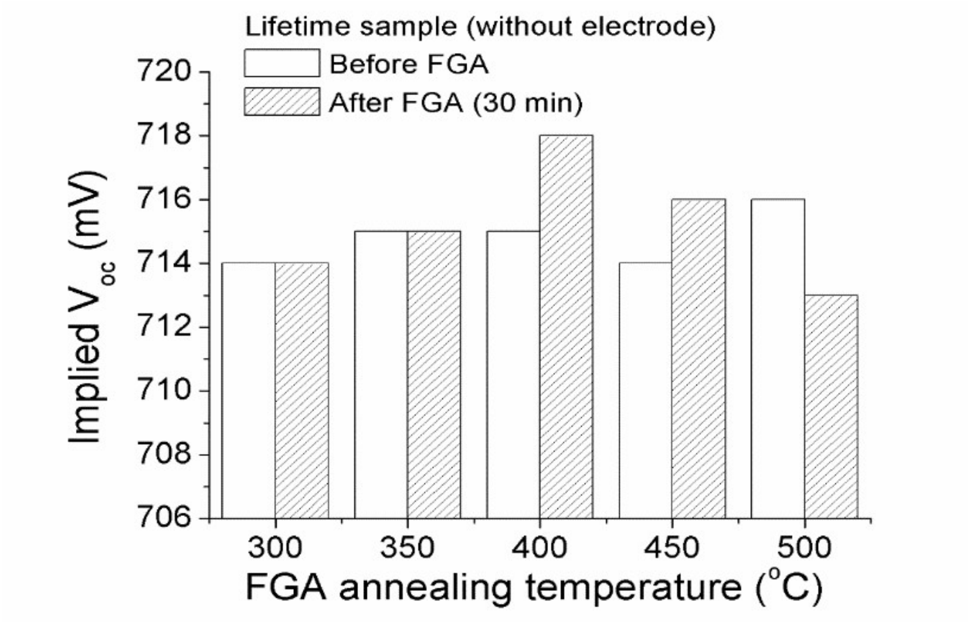

Figure S12. iV_{oc} as a function of the FGA annealing temperatures.

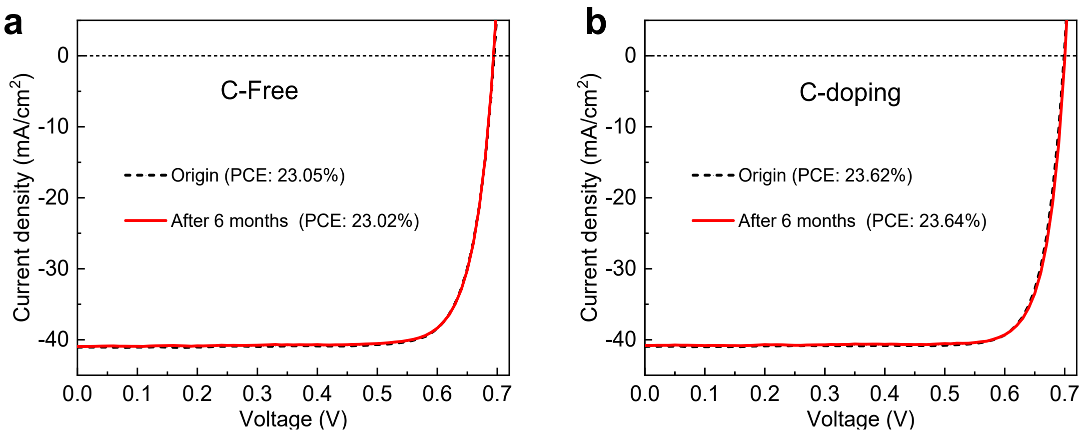

Figure S13. Light J–V curves for the (a) C-free and (b) C-doped samples after 6 months, where the original results are also presented as a reference.

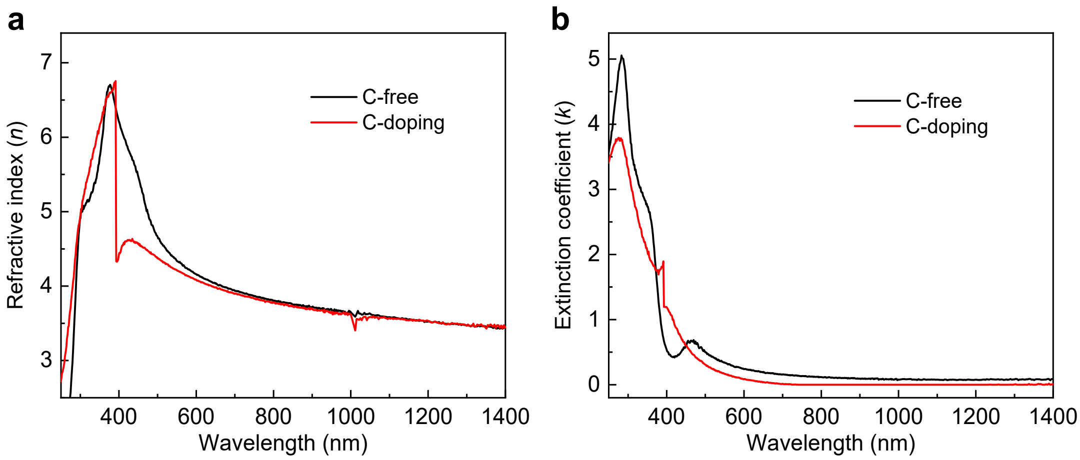

Figure S14. Refractive index of *n* and *k* as a function of wavelength.

Table S1. Summary of the previous related works using C doping and other strategies to suppress the blistering.

	Institution	Methods	Performance	Ref.
C-doping	EPFL	A fast thermal annealing nc-SiC_x(P):H	inhibit firing-induced layer delamination and hydrogen effusion; V_{oc}: 698 mV, 21.9% efficiency	1
	IEK5	hot-wire chemical vapour deposition nc-SiC:H(n)	high optical transparency good passivation a certified efficiency of 23.99%	2
	EPFL	PECVD SiC_x(p)	blistering-free; iV_{oc}: 718 mV p-type wafer; 21.9% efficiency	3
	CSEM	PECVD SiC_x(n) & SiCx(p)	high surface passivation and optical transparency iV_{oc}: 746 mV	4
	TUT	PECVD poly-SiCx	high passivation quality, high optical transparency at short wavelength, 20.17% efficiency	5
	IEK5	hot-wire chemical vapour deposition μc-SiC:H(n)	high optical transparency, J_{sc} > 42 mA/cm^2, iV_{oc} of 742 mV	6
	CNITECH	**PECVD C-doped *n*-type poly-Si**	**blistering-free; a high iV_{oc} exceeding 750 mV a high efficiency of 24.27% (a certified efficiency of 23.82%)**	**This work**
Other strategies to suppress blistering	UGA	place the samples in the furnace at low temperature; increase the gas flow ratio R = H_2/SiH_4	iV_{oc}: 734 mV	7
	Georgia Tech	Optimize precursor SiH_4/PH_3 flow rate, H_2 volume ratio and deposition power	iV_{oc}: 730 mV; J_0: 4.3 fA/cm^2; 21.2% efficiency on 239 cm^2 commercial wafers	8
	CEA-Liten	Optimize the poly-Si thickness, deposition temperature and gas flow ratio	iV_{oc}: 714 mV for poly-Si(p^+)	9
		Reduce the substrate heater	iV_{oc}: 733 mV, ρ_c: 90 mΩ·cm^2, an	

	IEK5	temperature	ultrafast deposition rate of 150 nm/min	10
	Korea Institute of Energy Research	Investigate the annealing temperature and duration, surface roughness, and deposition temperature	Approaching 700 mV iV_{oc}	11

Table S2. Crystallization fractions and residual stresses of poly-Si films under the different annealing temperatures.

Samples		C-free	light C-doping	moderate C-doping	excessive C-doping
840°C	crystallization fraction (%)	81.1	71.5	65.8	63.1
	residual stress (MPa)	-174.0	-290.8	-477.2	-1129.8
880°C	crystallization fraction (%)	82.5	73.1	67.4	64.2
	residual stress (MPa)	-29.4	-59.4	-437.2	-665.0
920°C	crystallization fraction (%)	84.8	74.4	70.1	66.7
	residual stress (MPa)	-44.4	-56.5	-133.7	-517.3

Table S3. The iV_{oc}, $J_{0,s}$ and τ_{eff} of double symmetrical poly-Si/SiO_x/c-Si structures under the different annealing temperatures.

Properties	T_a	C-free	light C-doping	moderate C-doping	excessive C-doping
iV_{oc} (mV)	840°C	739	744	745	743
	860°C	720	734	742	744
	880°C	708	711	740	750
	900°C	680	704	727	735
	920°C	668	672	706	719
$J_{0,s}$ (fA/cm^2)	840°C	2.2	1.6	2.2	2.3
	860°C	5.5	4.3	3.0	2.2
	880°C	24.7	14.4	2.9	1.6
	900°C	40	29.9	6.6	3.5
	920°C	72.0	62.0	17.6	9.1
τ_{eff} (ms) @ 1×10^{15} cm^{-3}	840°C	7.51	13.39	12.05	11.58
	880°C	3.2	2.98	9.95	15.36
	920°C	0.54	0.59	2.28	4.33

Table S4. Contact resistivity of poly-Si/SiO_x/c-Si junctions based on CS method under the different annealing temperatures (unit: mΩ·cm^2).

Samples	C-free	light C-doping	moderate C-doping	excessive C-doping
840^{o}C	14.8	25.6	45.7	66.5
880^{o}C	5.3	6.4	6.5	7.7
920^{o}C	2.9	3.7	5.9	7.0

Table S5. Sheet resistivity of poly-Si films with a thickness of 40 nm under the different annealing temperatures (unit: Ω/sq).

Samples	C-free	light C-doping	moderate C-doping	excessive C-doping
840^{o}C	108.1	118.0	125.5	161.2
880^{o}C	99.4	112.3	116.7	122.6
920^{o}C	83.2	99.3	109.2	111.1

Table S6. Mobility of poly-Si films under the different annealing temperatures (unit: cm^2/V/s).

Samples	C-free	light C-doping	moderate C-doping	excessive C-doping
840^{o}C	32.7	7.63	3.57	3.26
880^{o}C	27.8	8.07	4.82	4.03
920^{o}C	27.6	9.07	6.23	5.43

Table S7. Parameters used for the device simulation.

Parameters	Values
Bulk properties:	
Wafer thickness, W (μm)	170
Wafer resistivity, ρ (Ω·cm)	1
Background bulk Lifetime, τ_{bulk} (ms)	50
Auger recombination	Richter model
Radiative recombination	Nguyen model
Mobility	Klaassen model
Bandgap narrowing	Schenk model
Front metal grid:	
Space between fingers (μm)	600
Finger width (μm)	10
Front of P^+ emitter:	
Sheet resistance, R_{sheet} (Ω/sq)	105
$J_{0e,\ met\ contact}$ (fA/cm^2)	80
$J_{0e,\ pass}$ (fA/cm^2)	100
Contact resistivity ρ_c (mΩ·cm^2)	0.1
Junction depth (nm)	850
Rear poly-Si:	
J_0 (fA/cm^2)	Experiment
ρ_c (mΩ·cm^2)	Experiment
Parallel resistance R_p (kΩ·cm^2)	20
Series resistance R_s (Ω·cm^2)	0.1
Optical model:	
Passivation & Reflectance Layer (nm)	Experiment
Shading width of fingers	100%

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