Faculty of Engineering
School of Photovoltaic and Renewable Energy Engineering

Optical Optimization for III-V//Si Multijunction Solar cells

ASIA-PACIFIC SOLAR RESEARCH CONFERENCEDEC

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Caixia Li, Ziheng Liu, Pengfei Zhang, Xin Cui, Kaiwen Sun, N.J. Ekins-Daukes and Martin Green, Xiaojing Hao

School of Photovoltaic and Renewable Energy Engineering, University of New South Wales (UNSW), Sydney, NSW 2052, Australia

❑Background

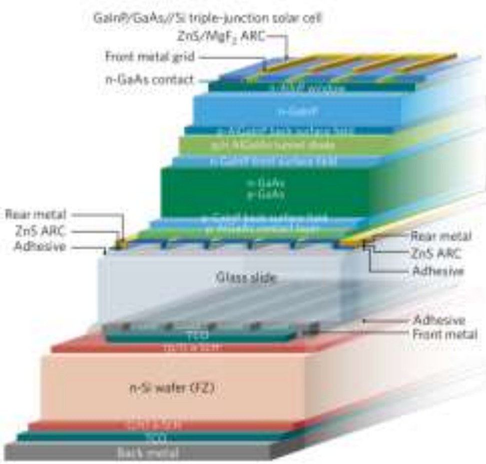
❑Transparent conductive adhesives(TCA) layer for 2-terminal III-V//Si multijunction solar cells

- Optical transparency
- Electrical conductivity

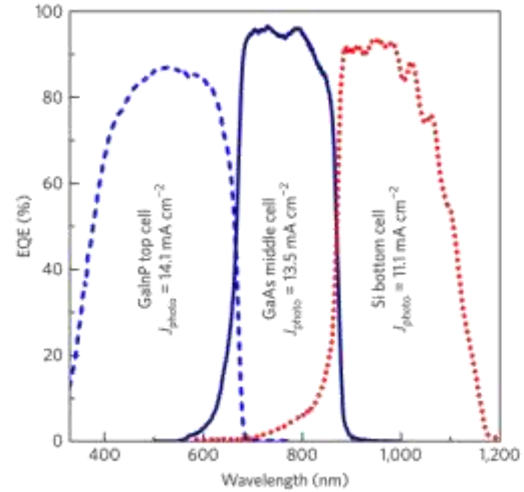
❑Optical optimization of 4-terminal III-V//Si multijunction solar cells

- Photon recycling to further improve performance
- Optical transparency of long wavelength photons

❑ Multijunction solar cell: broader solar spectrum



GaInP/GaAs//Si triple-junction solar cell[1]



EQE of GaInP/GaAs//Si solar cell[1]

❑ Why chose III-V and Silicon

- Si: low cost/mature industrial technology---but reaching efficiency limit
- III-V tandem: highest efficiency---but high cost
- III-V/Si tandem: high efficiency & low cost

[1]Nature Energy, 2017, 2(9): 17144.

Background

❑ The <u>approaches</u> to obtain III-V/Si tandem solar cell:

- Epitaxy growth
- <u>Non-epitaxy growth:</u>

  2-terminal via bonding

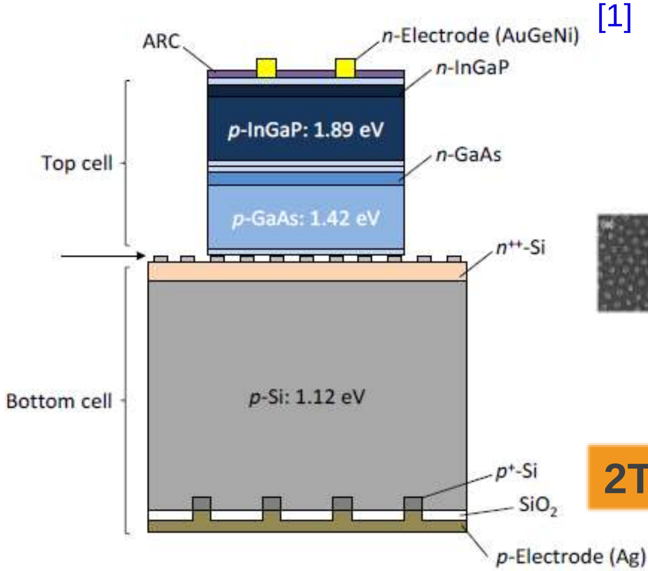
  4-terminal mechanically stacking

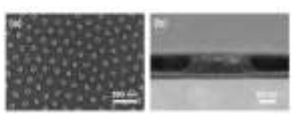
❑ The <u>advantages</u> of Non-epitaxy route :

- Lattice-mismatched subcells
- Individual process for each cell
- Current matching can be ignored in 4 terminals

❑ 2-Terminal and 4-Terminal III-V//Si multijunction solar cells

[1]





2T

4T

[2]

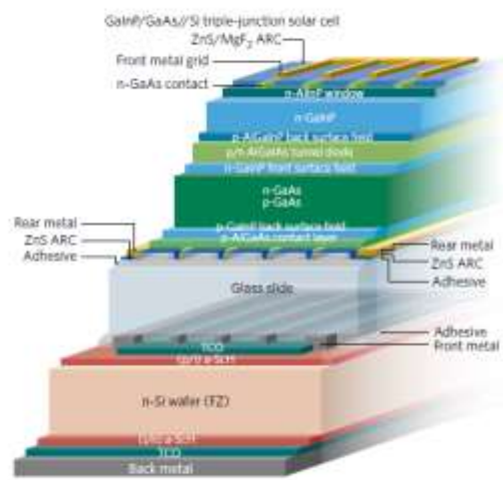


Figure 3 | Design of the four-terminal GaInP/GaAs//Si triple-junction solar cell. The GaInP top and GaAs middle cell are connected via a tunnel junction and stacked on a Si heterojunction solar cell (the schematic is not to scale).

[1]Applied Physics Letters 101.19 (2012): 191111.
[2]Nature Energy, 2017, 2(9): 17144.

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Background

❑ Current status in III-V//Si multi-junction solar cells

	Structure	Top cell efficiency	Bottom cell efficiency	Total efficiency	Boding method
4T	GaInP//Si	20%	13.26%	32.45%	Epoxy + glass[1]
	GaAs//Si	26.8%	9.68%	32.82%	
	GaInP/GaAs//Si	30.01%	7.27%	35.91%	
2T	GaInP/GaAs//Si	N/A		30.93%	Epoxy + glass[1]
	InGaP/GaAs//Si	N/A		25.10%	Pd array[2]
	GaInP/InGaAs//Si	N/A		25.5%	Ti /Pt/Au[3]
	GaInP/GaAs//Si	N/A		33.3%	Surface-activated wafer bonding[4]

❑ Proper TCA layer required for 2-Terminal III-V//Si multijunction solar cells

- Optical losses for bottom cell
- Electrical losses introduced by intermediate layer

[1] Essig S, Allebé C, Remo T, et al.Nature Energy, 2017, 2(9): 17144.
[2] Mizuno H, Makita K, Tayagaki T, et al. Applied Physics Express, 2017, 10(7): 072301.
[3] Yang J, Peng Z, Cheong D, et al. IEEE Journal of Photovoltaics, 2014, 4(4): 1149-1155.
[4] Cariou R, Benick J, Feldmann F, et al. Nature Energy, 2018, 3(4): 326.

TCA for 2-terminal III-V//Si multijunction solar cells

Transparent adhesive
+
Conductivity

Transmission >80%

Trade off

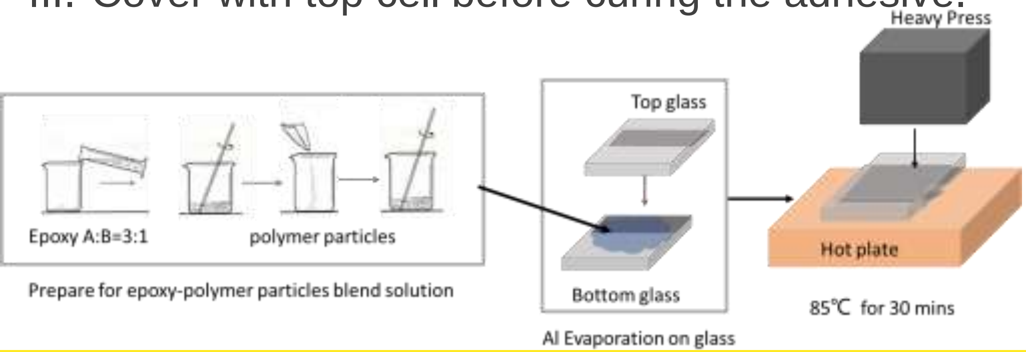
Electrical losses < 1%

Optimum density of microsphere

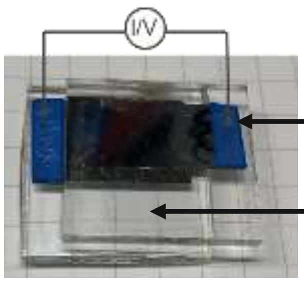
Materials selection | Performance requirement | Research objective

☐ TCA fabrication process:

I. Prepare Epoxy and metal particles/wires mixture.
II. Uniform coverage on the bottom cell surface.
III. Cover with top cell before curing the adhesive.



☐ Optical/electrical measurement:



Resistance measurement:
4-point

Optical measurement:
sample without Al contact
as reference

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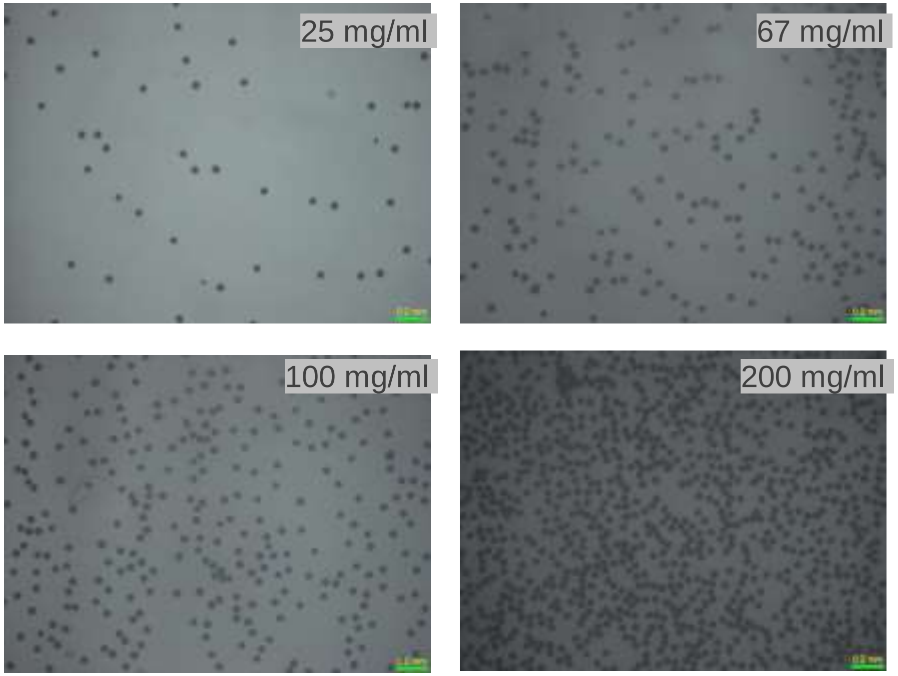
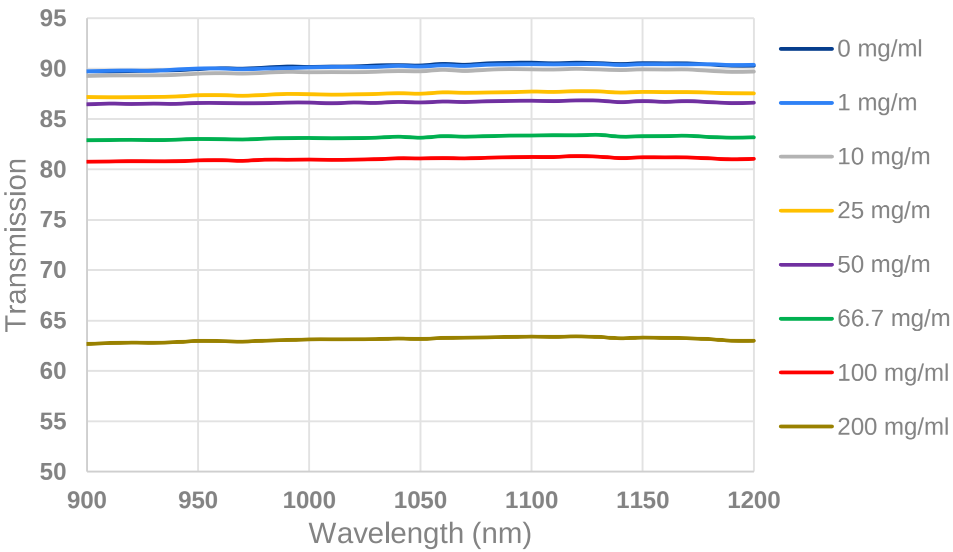
TCA for 2-terminal III-V//Si multijunction solar cells

☐ Optical characteristic of TCA layer



Microscopy images of different density of microsphere in epoxy gel.

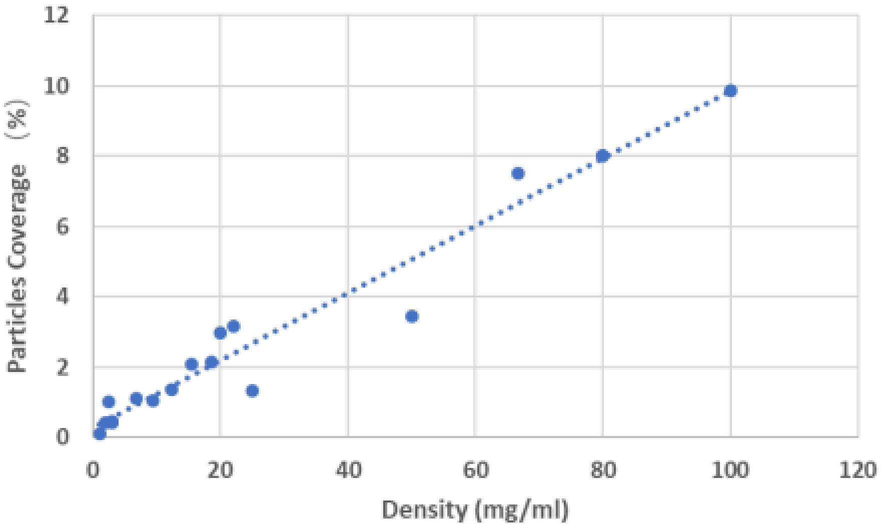


Transmission of different density of microsphere in epoxy gel.

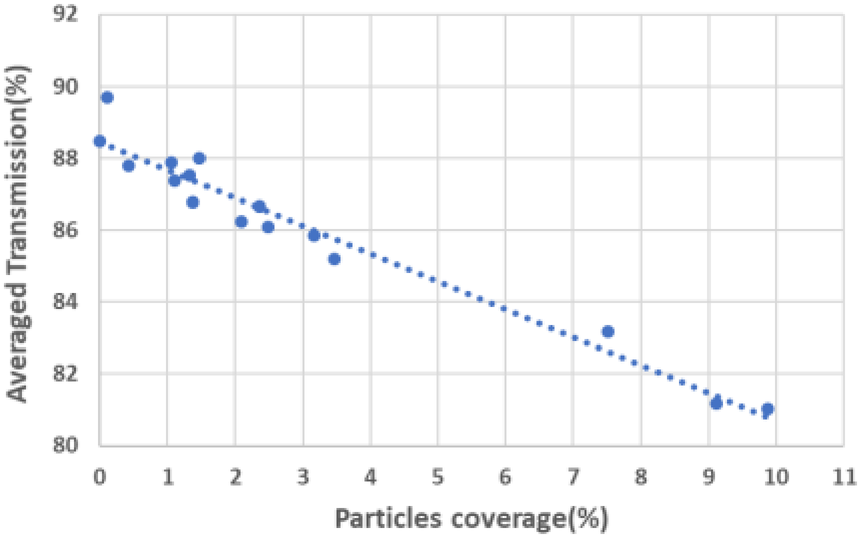
➢ Transmission measurements with varying microsphere density show reduced transmission with increasing percent area coverages of microspheres in long wavelength (900~1200nm).

TCA of 2-terminal III-V//Si multijunction solar cells

☐ The linear relationship between microsphere density, coverage and transmission



Microsphere Density VS Particles Coverage



Particles Coverage VS Averaged Transmission

- The relationship between T,A and d are got to further analysis performance of this TCA on multijunction solar cell:

T = -0.7749*A + 88.451
(R^2 = 0.9547)

A = 0.0957*d + 0.2718
(R^2 = 0.9594)

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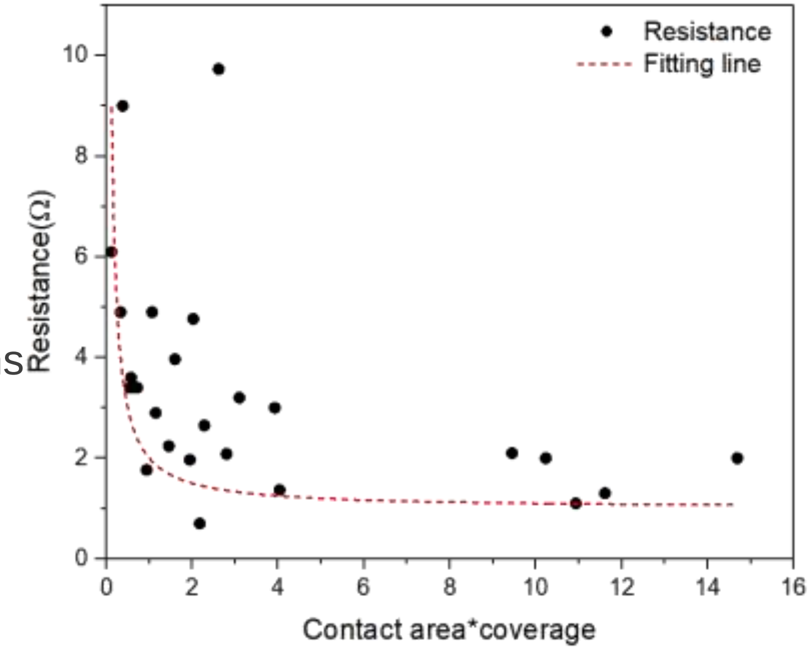
□ Electrical characteristic and optimum parameters

$$\mathrm{R} = \frac{\rho l}{S_m A} = \frac{k_1}{S_m A}$$

R : Resistance measured
S_m: contact area
A : percent area coverages of microspheres

R and $A \cdot S_m$ are reciprocal relations
$k_1 \approx 1$

$T = T_{max} - k_2 A$ $T_{max} = 0.88, k_2 \approx 0.75$



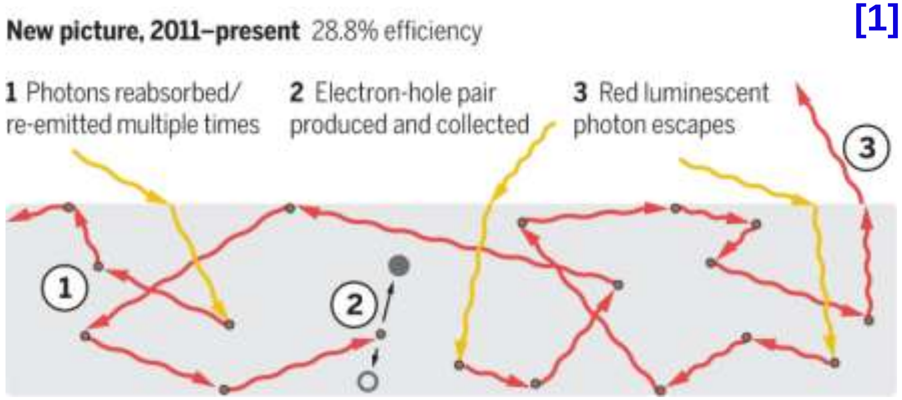
➢ After consider the trade off between optical and electrical property, optimal area coverage of microsphere is obtained:

$$\mathrm{A}^{optimum} = 5.6\%$$
$$(V_{oc} = 3.2V, I = 0.01\ {}^{A}/_{cm^2})$$

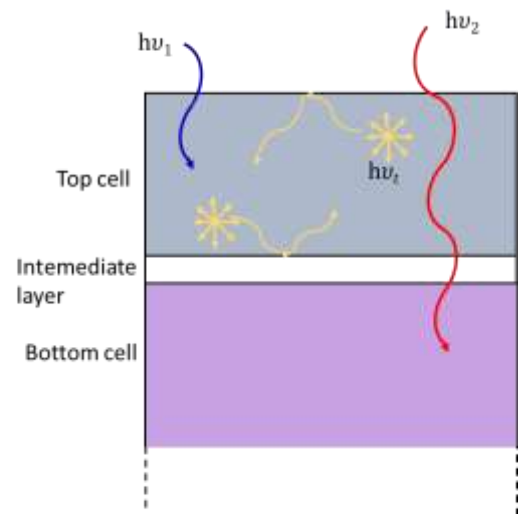
Optical optimization of 4-terminal III-V//Si multijunction solar cells

☐ Photon recycling in 4-Terminals III-V//Si multijunction solar cell

[1]



Photon recycling in single junction III-V solar cell

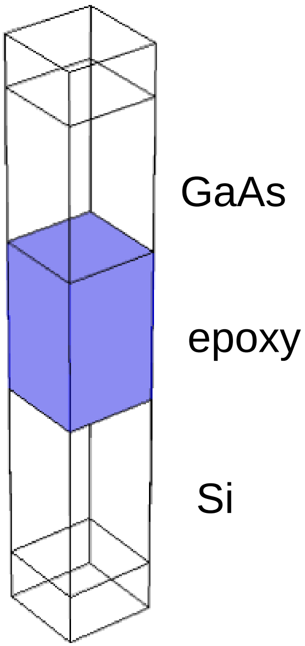
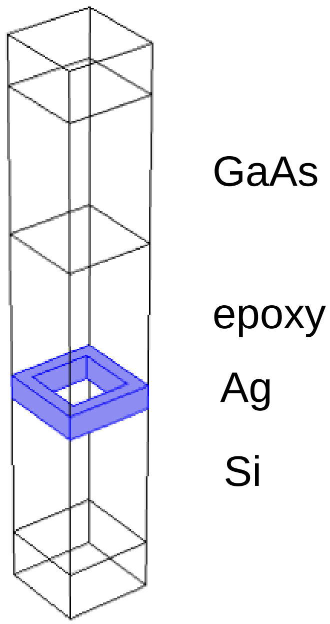
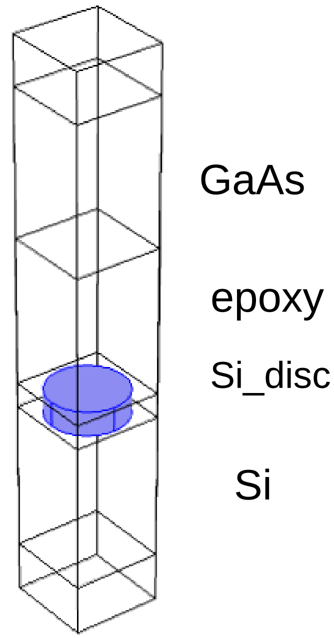
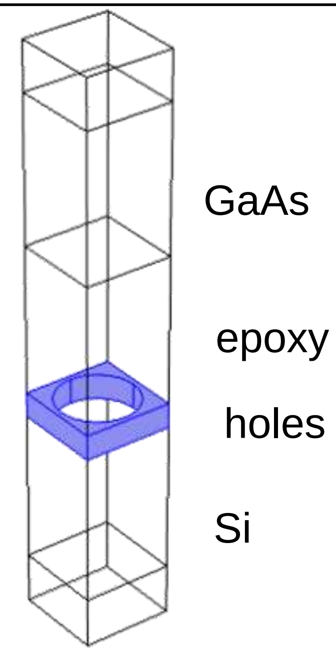


Photon recycling effect in 4 terminals III-V//Si multijunction solar cells

☐ Main losses:

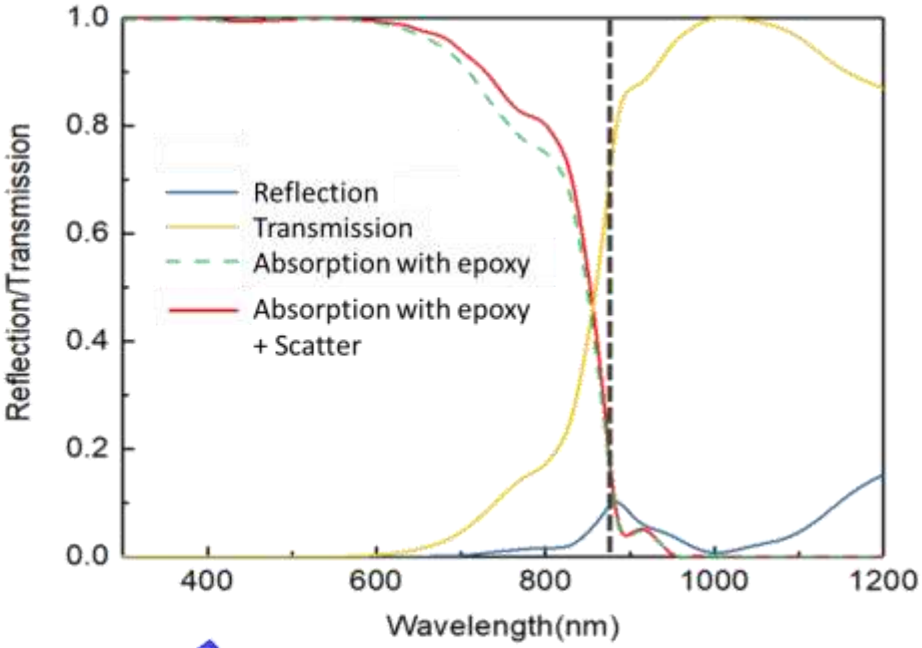
- Top cell: efficiency is ~2% lower compared with metal back single cell
  - ⟶ Photon recycling required
- Optical losses introduced by intermediate layer
  - ⟶ Long wavelength transmission required

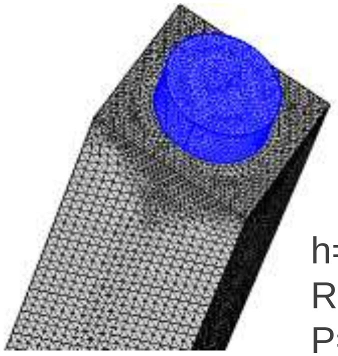
Basic structures

Epoxy	Epoxy + Metal	Epoxy + Si_disc	Epoxy + holes
			
GaAs/epoxy/Si	GaAs/epoxy/Ag/Si	GaAs/epoxy/ Si_disc/Si	GaAs/epoxy/ holes/Si

*** The model represents the simplified structure of tandem solar cells.**

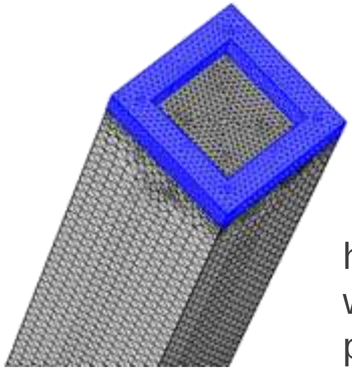
Optical optimization of 4-terminal III-V//Si multijunction solar cells





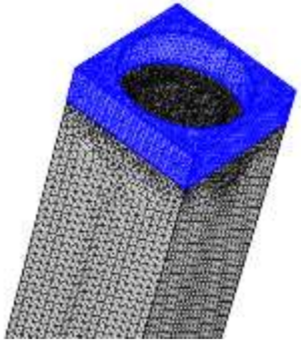
h=30 nm
R=40 nm
P=180 nm

Silicon disc
Nano imprinting technology



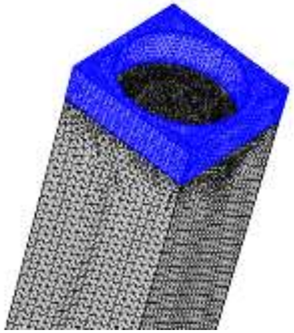
h=50 nm
w=180 nm
p=220 nm

Ag



h=30~50 nm
R=60-90 nm
P~2*R

TiO_2 holes



h=50 nm
r=80 nm
P~2*r

Silicon holes

Optical optimization of 4-terminal III-V//Si multijunction solar cells

I. Ag and Silicon disc

$$J_{sc} = Q \times \int \Phi(\lambda) \times abs \times \frac{1}{\Delta\lambda}\, d(\lambda)$$

No.	Jsc_top	Jsc_bottom	Jsc_total	parameters	Enhancement factor
1	28.59	13.50	42.09	GaAs/epoxy/Si	reference
9	29.82	13.53	43.35	Ag	1.26
19	28.83	14.30	43.12	Si_disc:h30_r40_p180	1.03
103	29.73	13.31	43.04	9+19	0.95

II. Silicon Holes array

NO.	Jsc_top	Jsc_bottom	Jsc_total	parameters	Enhancement factor
35	28.71	14.25	42.96	Si_holes: h=30 r=80 p=180	0.87
36	28.68	14.42	43.10	Si_holes: h=50 r=80 p=180	1.01
37	28.57	14.22	42.79	Si_holes: h=70 r=80 p=180	0.70

III. TiO_2 Holes array

NO.	Jsc_top	Jsc_bottom	Jsc_total	parameters	Enhancement factor
34	28.83	14.31	43.14	TiO2_holes (h=30 r=80 p=180)	1.05
38	28.92	14.29	43.20	TiO2_holes (h=50 r=80 p=180)	1.11
40	28.91	14.29	43.20	TiO2_holes (h=50 r=89 p=200)	1.11
41	28.92	14.29	43.21	TiO2_holes (h=50 r=71 p=160)	1.12
42	28.93	14.29	43.21	TiO2_holes (h=50 r=67 p=150)	1.12

Summary

- **TCA layer for 2 terminals III-V//Si multijunction solar cells**
  - Relationship obtained between microsphere density, coverage percent, transmission and Resistance
  - Optimized density of microsphere for high efficiency III-V//Si multijunction solar cell

- **Intermediate layer design to get high efficiency in 4 terminals III-V//Si multijunction solar cells**
  - Ag nanostructure, Silicon disc and TiO_2 hole array show evident improvement in top cell or bottom cell

Acknowledge

ARENA
Australian Government
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ACAP

Thanks for your attention