Advances in Epitaxial GaInP/GaAs/Si Triple Junction Solar Cells


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2) Philipps University Marburg
3) TU Ilmenau

IEEE PVSC-47 Virtual conference

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III-V on Si
Motivation

- Silicon solar cells
  - Limited to 29.4 % efficiency[1)]
  - Low cost of manufacturing

- III-V multi-junction solar cells
  - Highest efficiencies (38.8 %)[2)]
  - Proven stability (space)
  - Substrates costly

https://www.pv-tech.org/news/new-nrel-study-details-us-rooftop-solar-pv-potential-at-1118gw-plus

https://sci.esa.int/web/solar-orbiter/-/solar-orbiter-antenna-deployment

1) Richter et al. *IEEE Journal of Photovoltaics*, 4, 3, 2013
2) Chiu Pt et al., *Proc. 40th IEEE Photovoltaic Specialist Conference*, Denver, June 2014; 11–13

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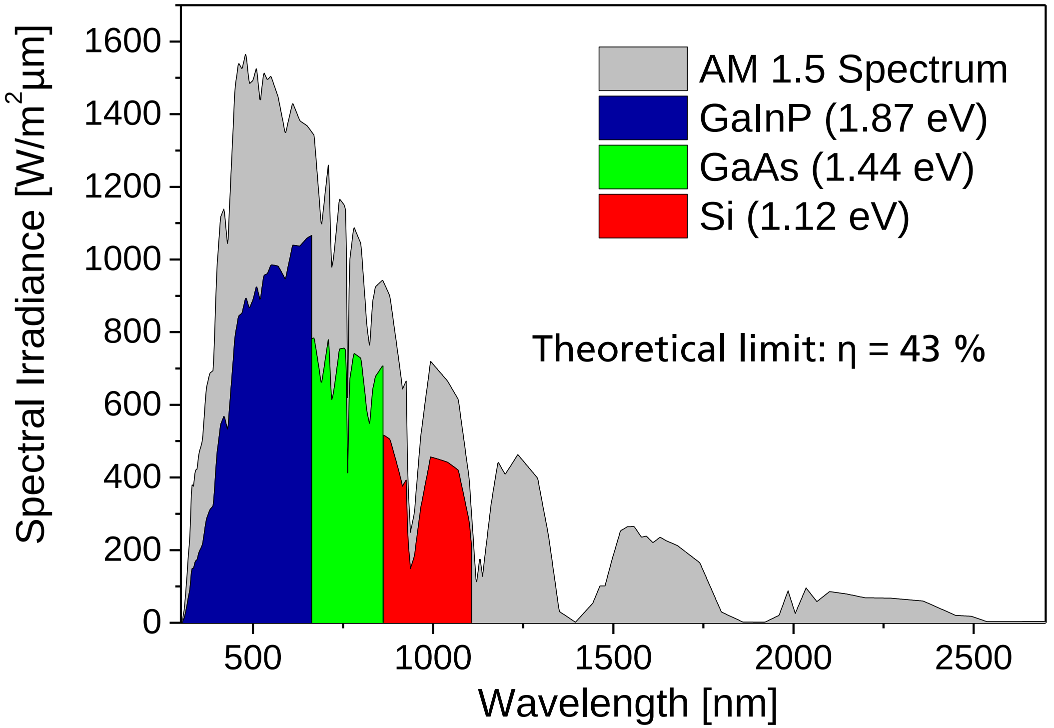

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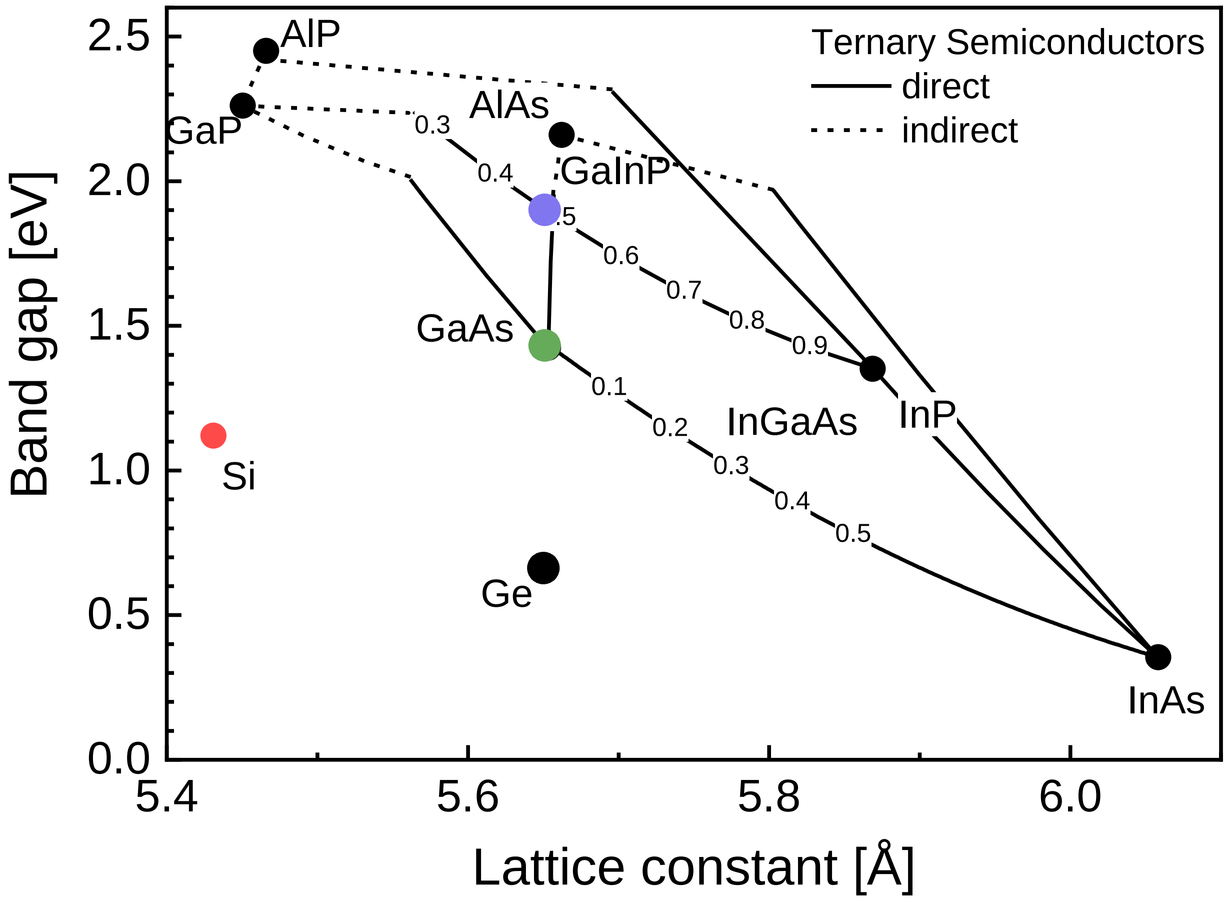
III-V on Si

Challenges

- III-V on Si
  - Polar (III-V) on non-polar (Si) crystals
  - Lattice mismatch of ~4%

→ III-V epitaxy on Si not trivial



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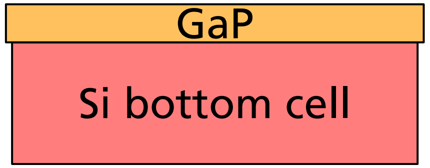
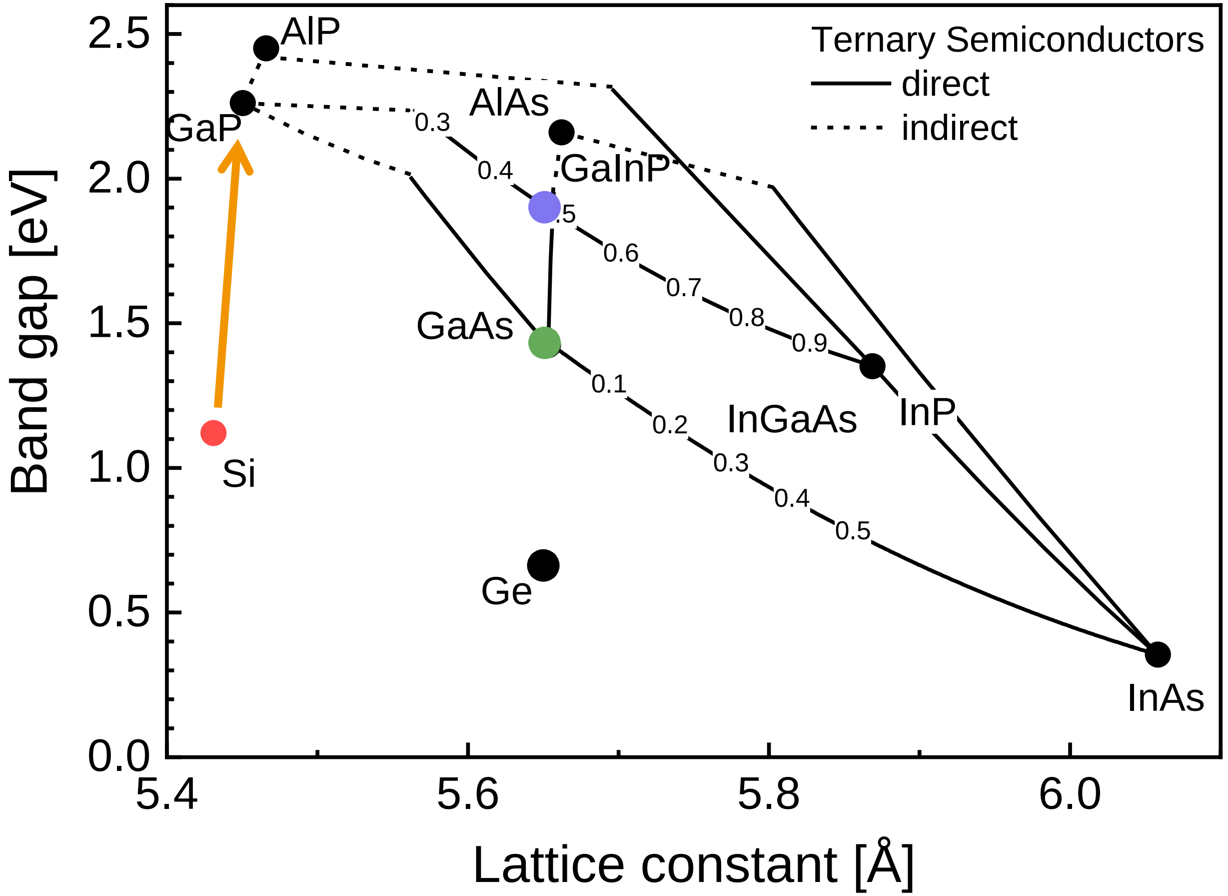
III-V on Si
MOVPE Approach





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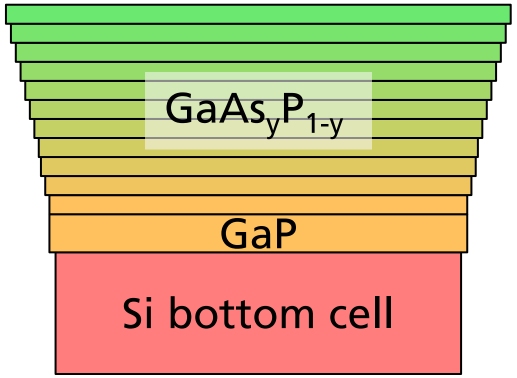

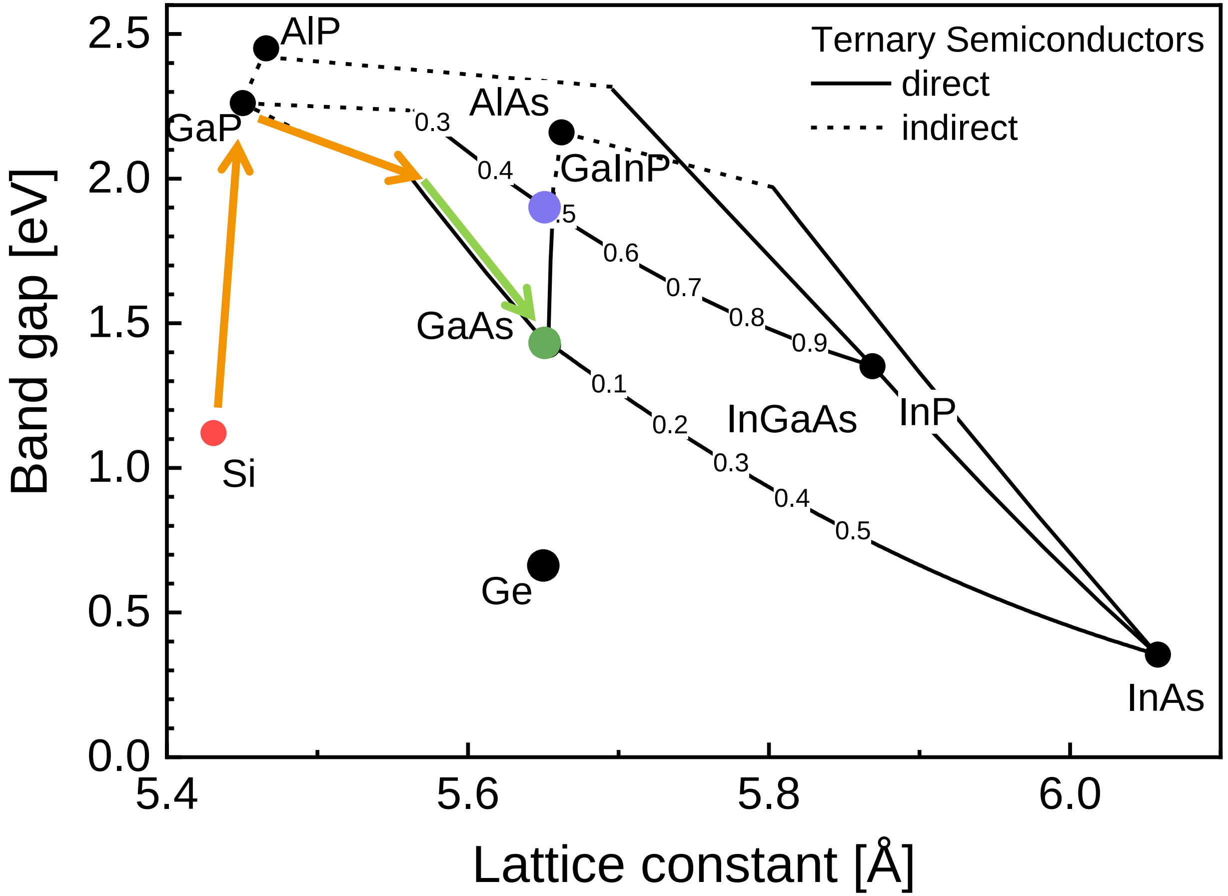

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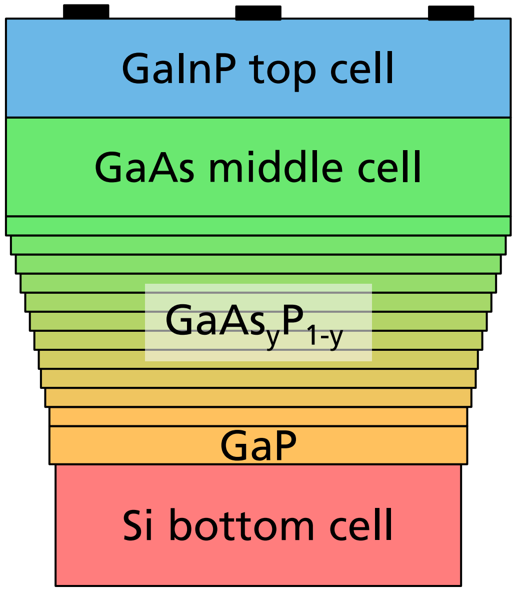
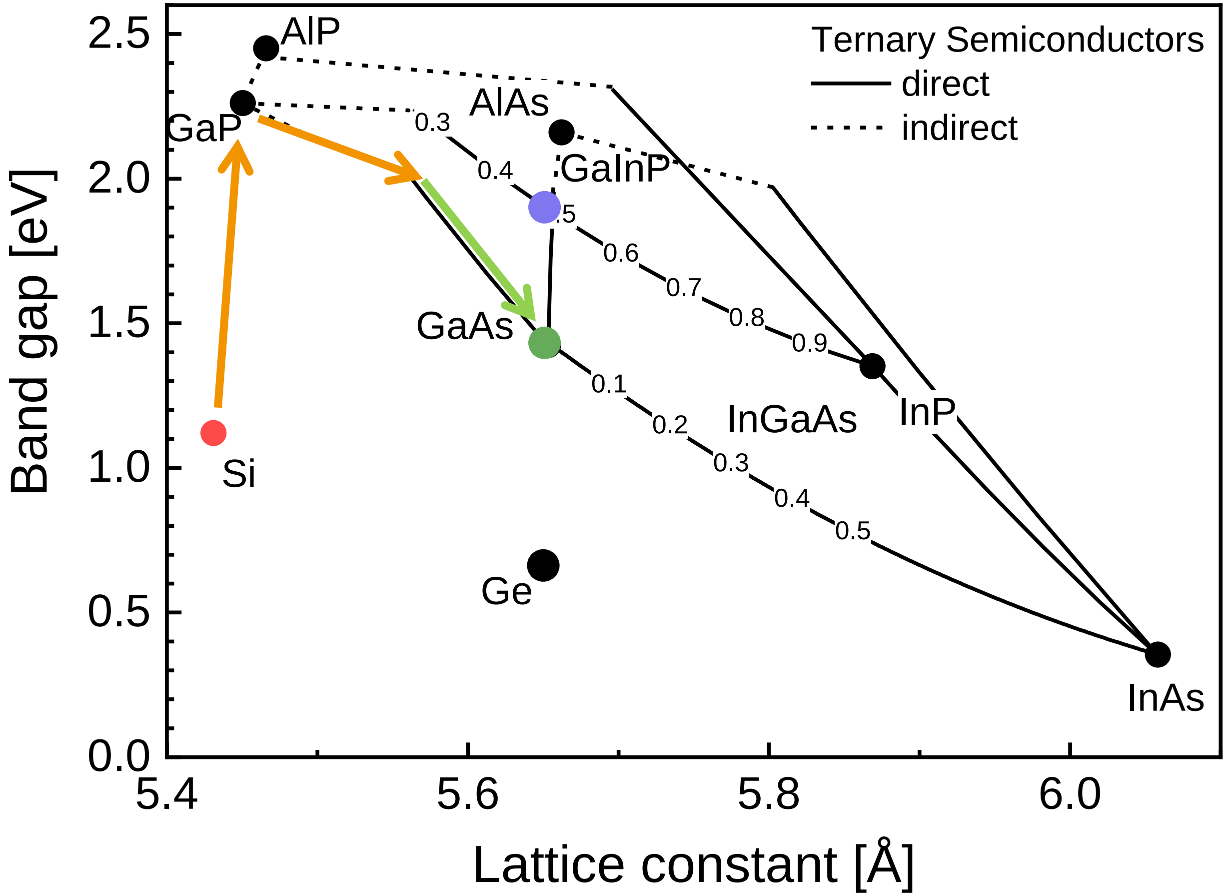
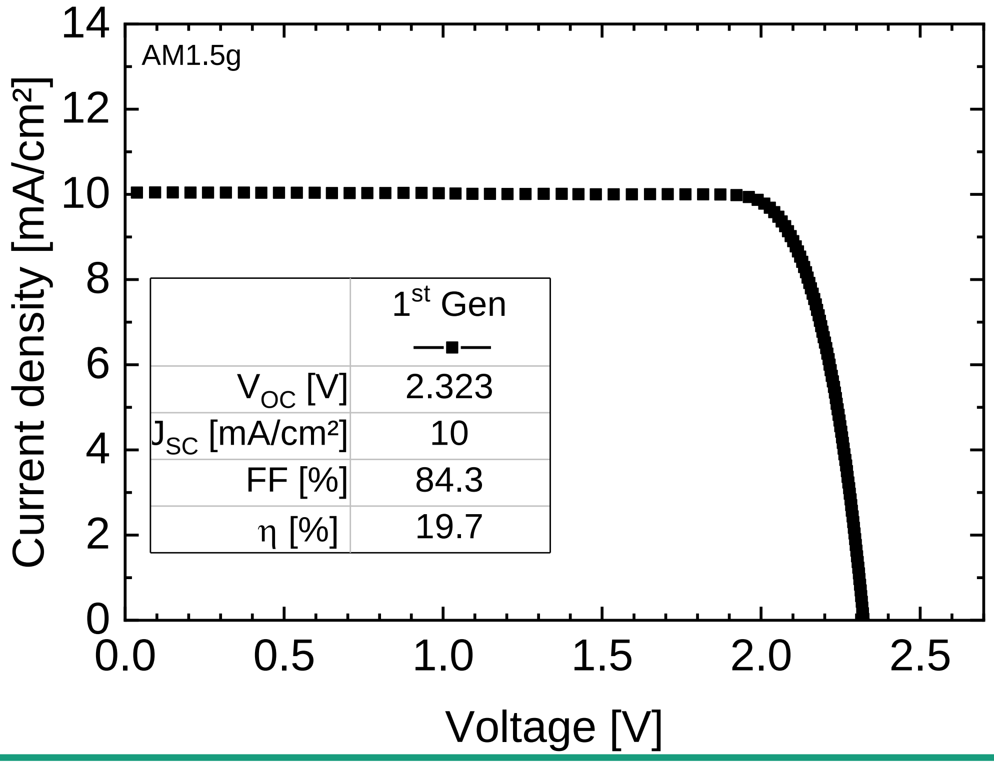


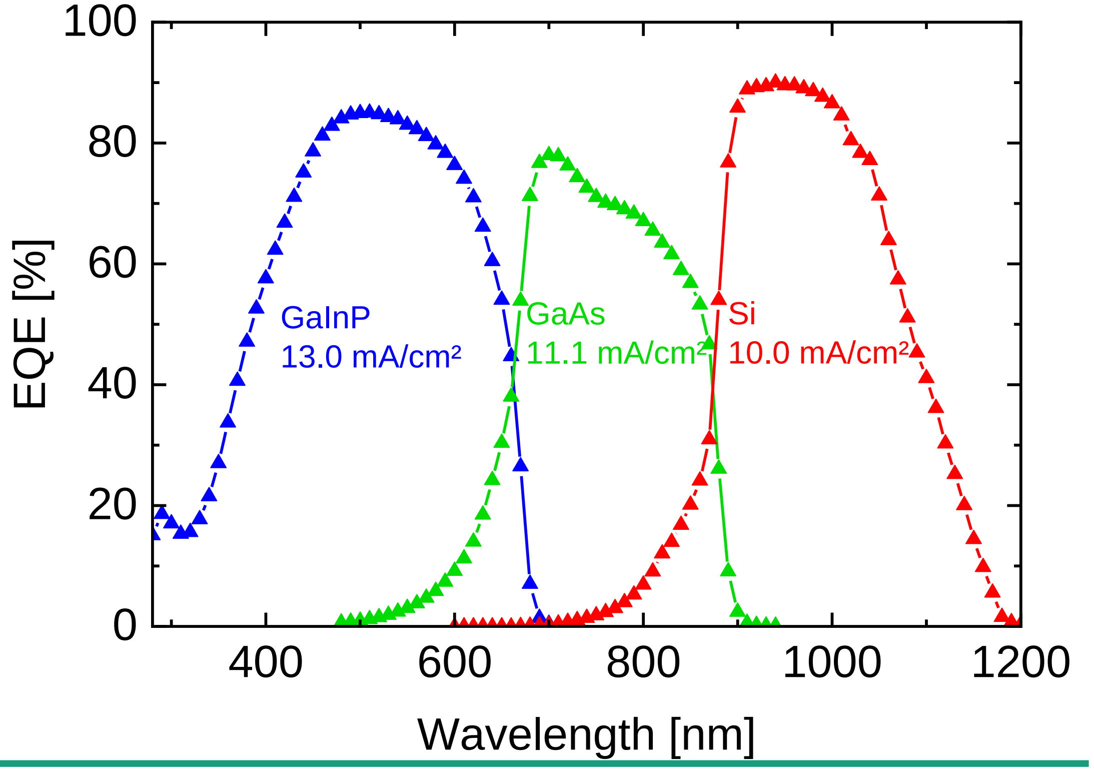


1^{st} Gen III-V on Si Solar Cell (2017)

Characterisation

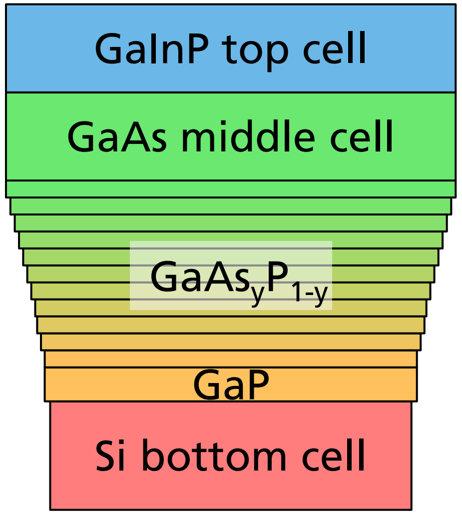
- Crystal defects limit voltage and quantum efficiency (TDD : 1.4×10^8 cm^{-2})

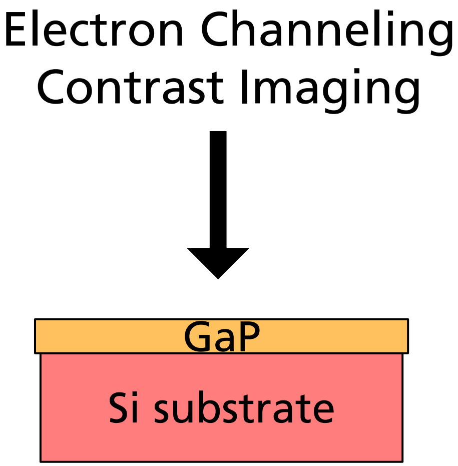




1^{st} Gen III-V on Si Solar Cell
Defect Characterisation

- Crystal defects limit voltage and quantum efficiency (TDD : 1.4×10^{8} cm^{-2})
- GaP nucleation on Si
  - Stacking fault pyramids 6×10^{7} cm^{-2}





Feifel et al. *Journal of Crystal Growth*, vol. 532, p. 125422, 2020

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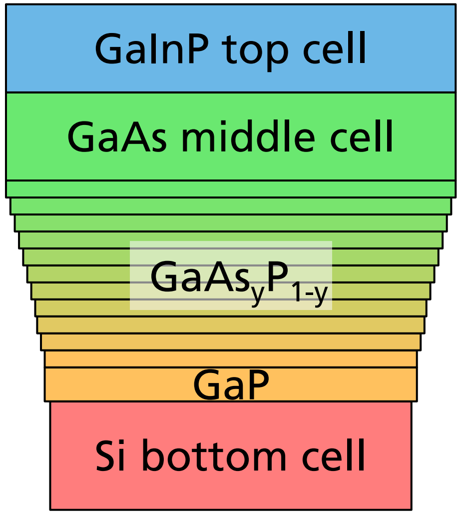

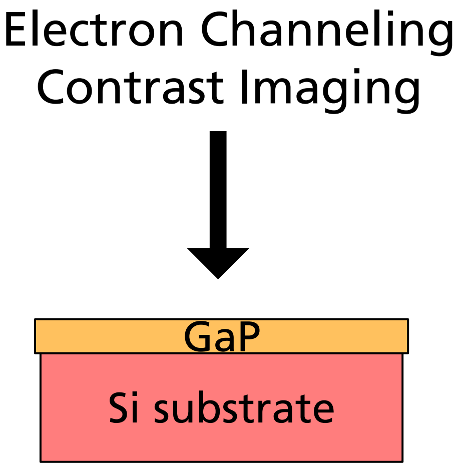

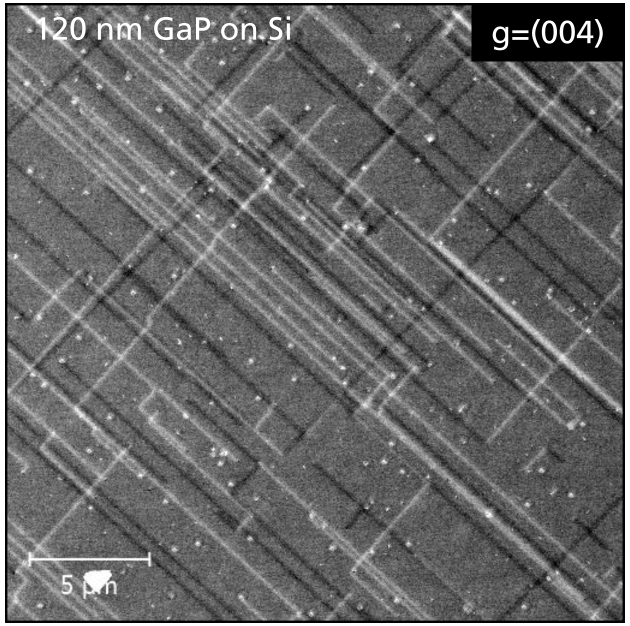

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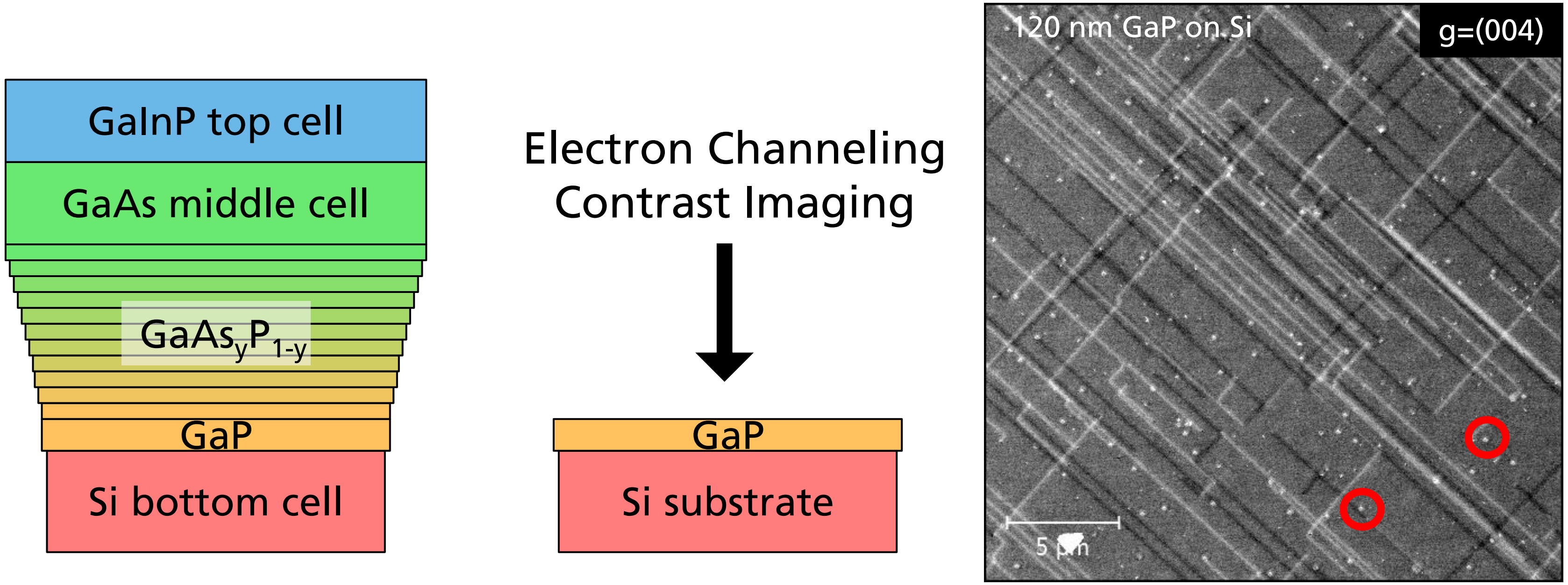

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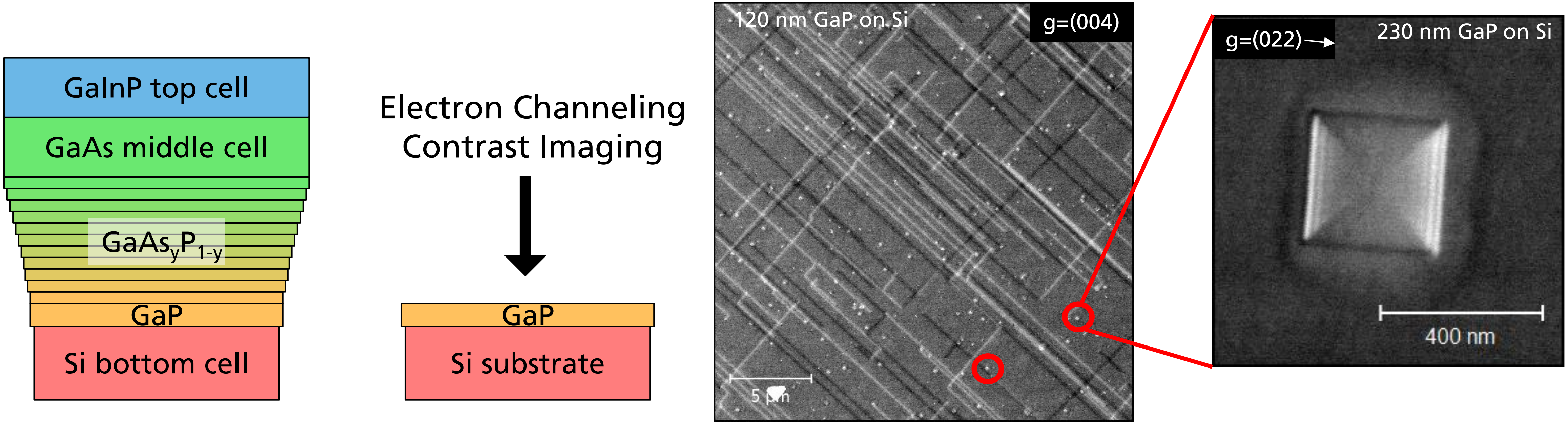

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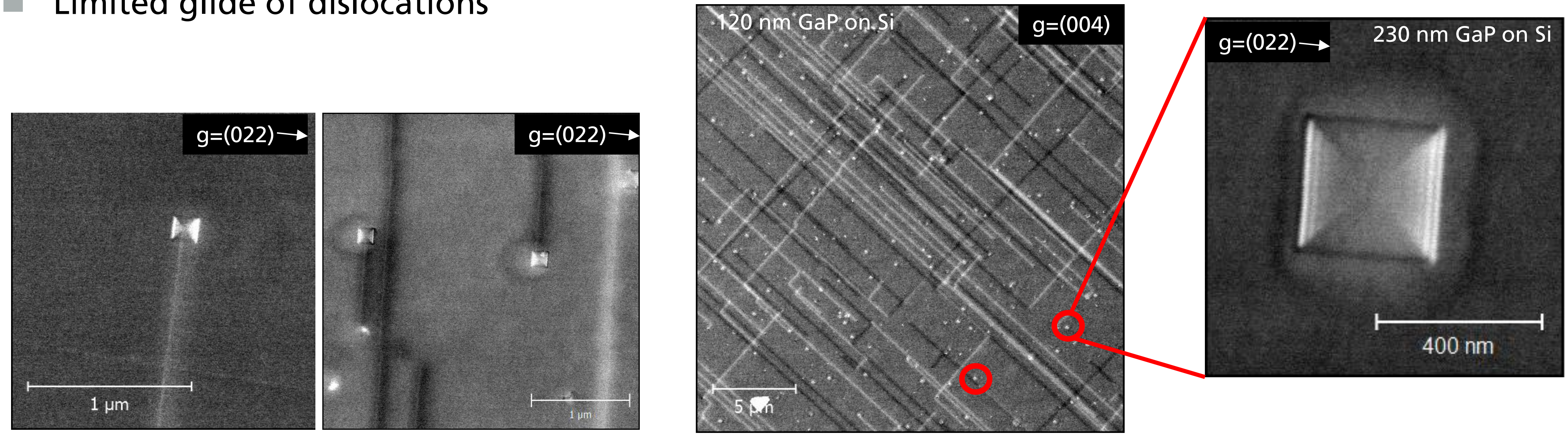

Feifel et al. *Journal of Crystal Growth*, vol. 532, p. 125422, 2020

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1^{st} Gen III-V on Si Solar Cell
Reduction of Defect Density

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  - Stacking fault pyramids 6×10^{7} cm^{-2}
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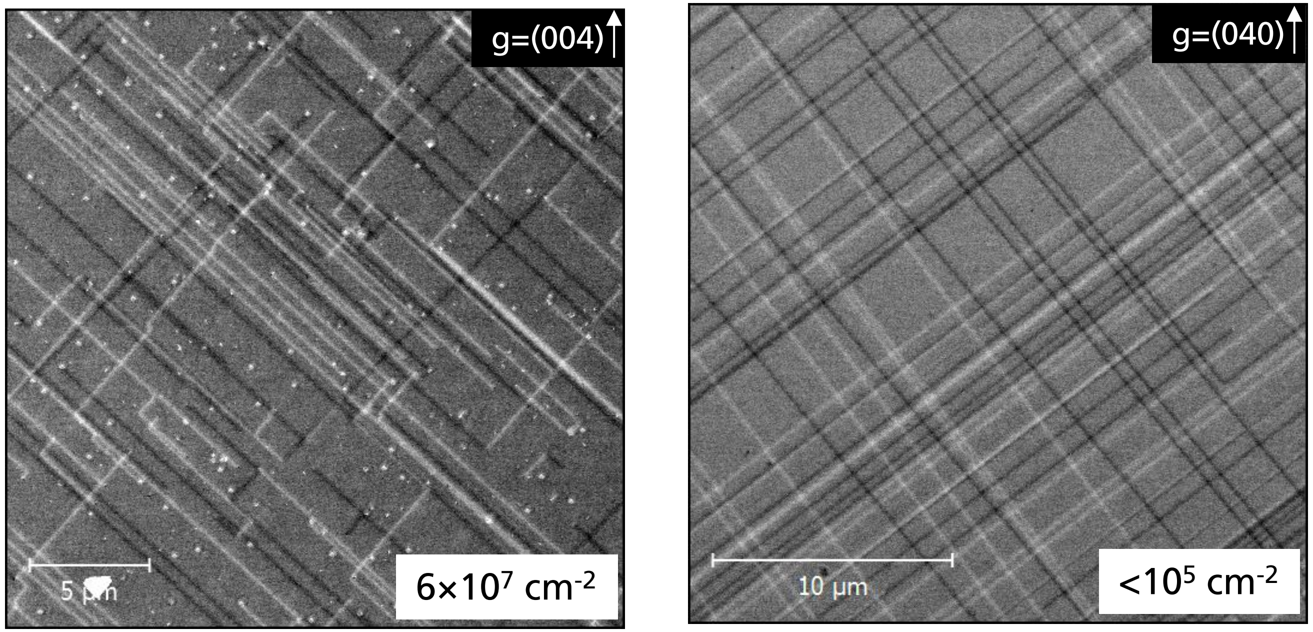
Optimization of GaP nucleation

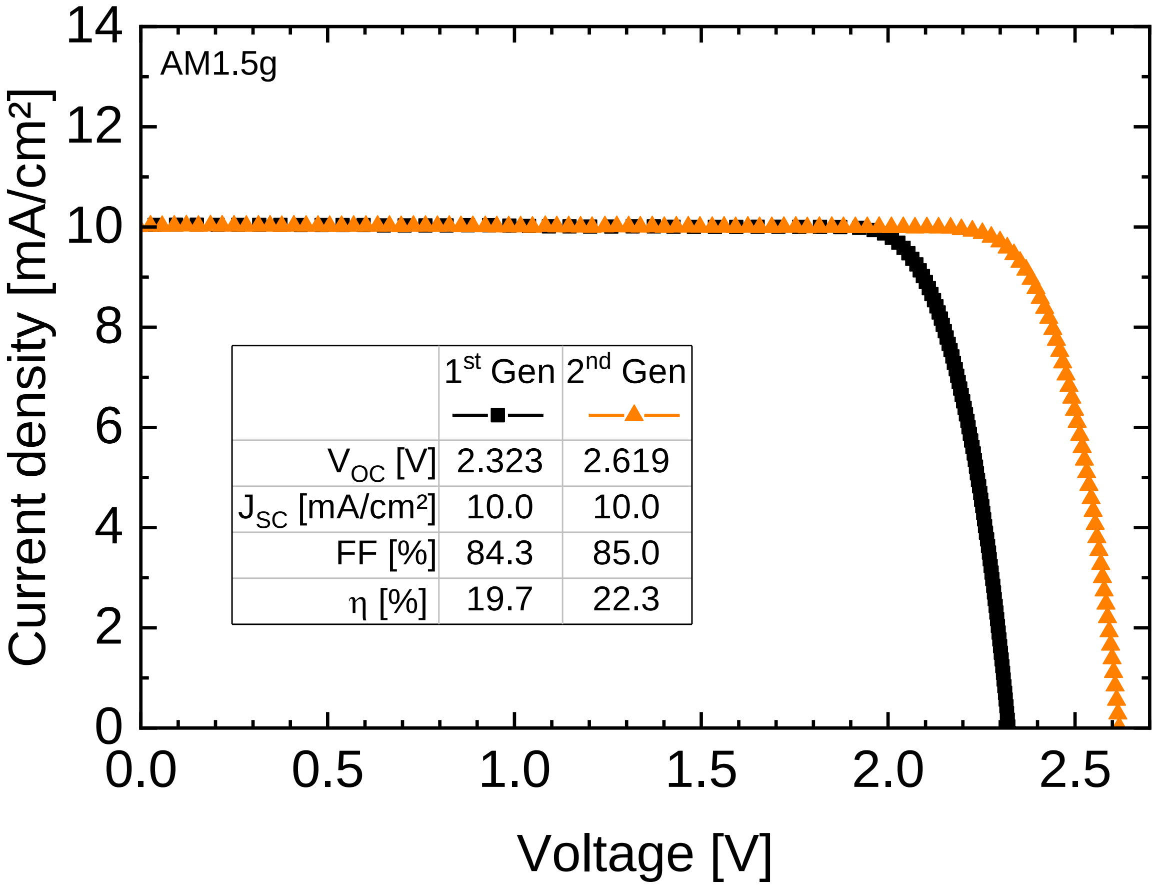


Feifel et al. *Journal of Crystal Growth*, vol. 532, p. 125422, 2020

2nd Gen III-V on Si Solar Cell (2019)

IV-Characteristics

- IV:
  - Increase in V_{OC} by +296 mV
  - No change in J_{SC}



Feifel et al. *Solar RRL*, vol. 3, p. 1900313, 2019

2^{nd} Gen III-V on Si Solar Cell
EQE

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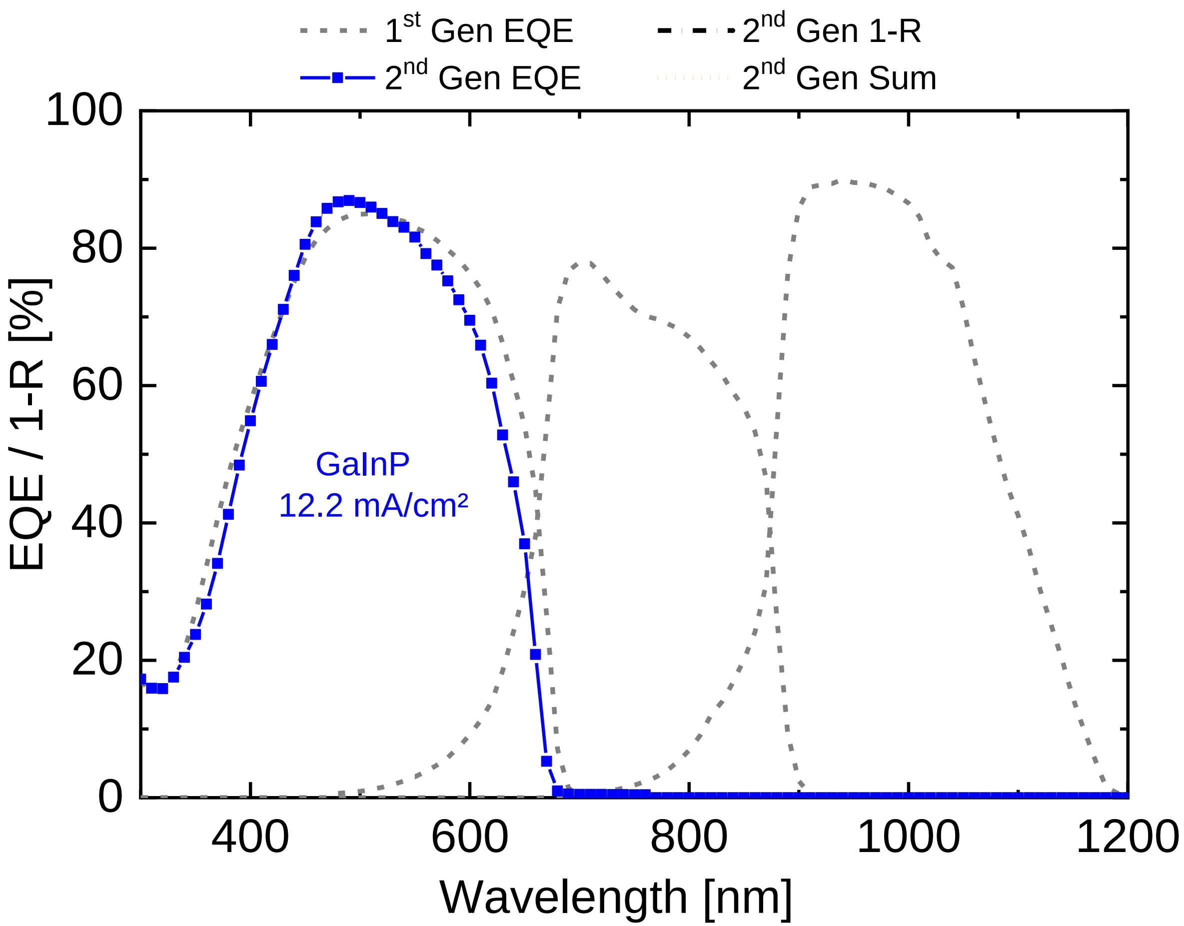
- EQE:
  - GaInP bandgap adjusted



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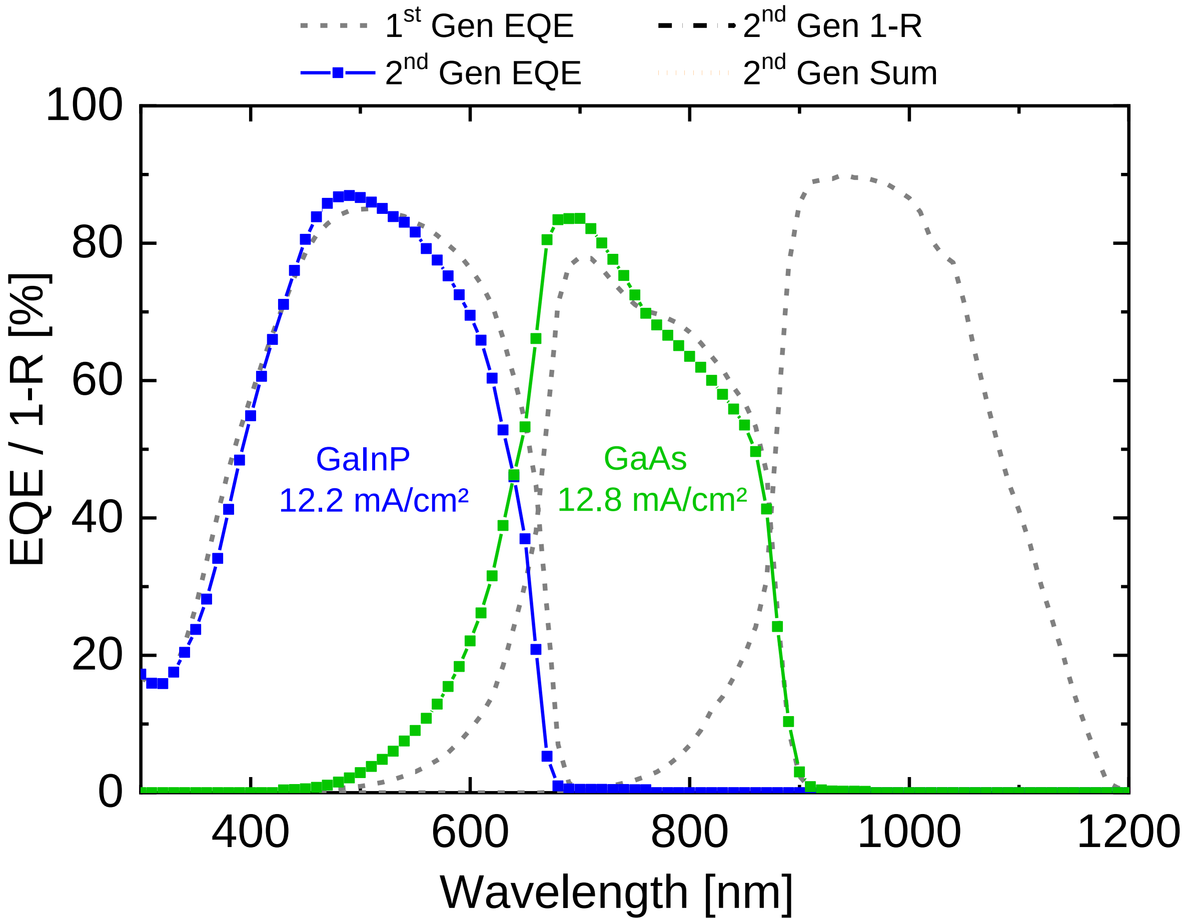
  - Thinner GaAs cell (760 nm vs 1200 nm) with higher EQE



Feifel et al. *Solar RRL*, vol. 3, p. 1900313, 2019

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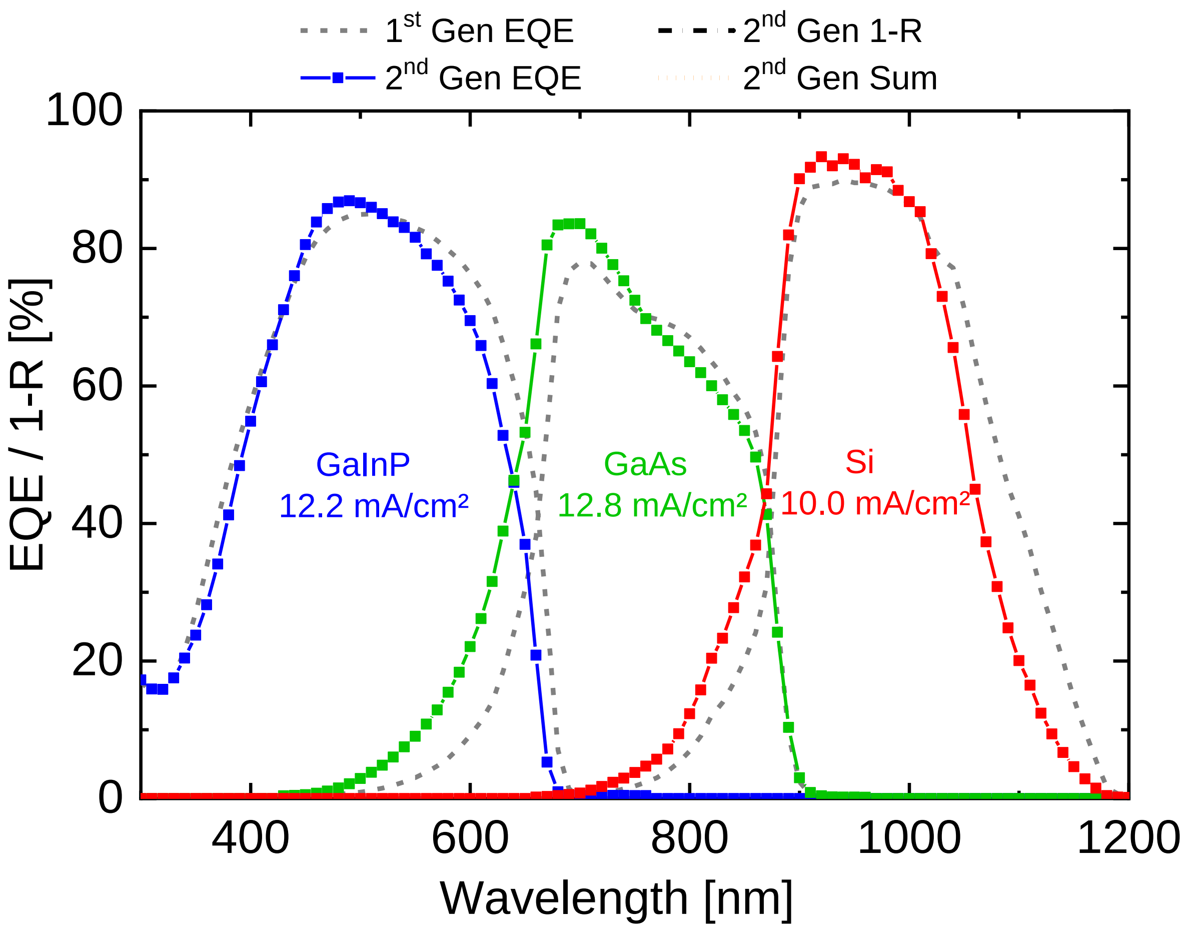

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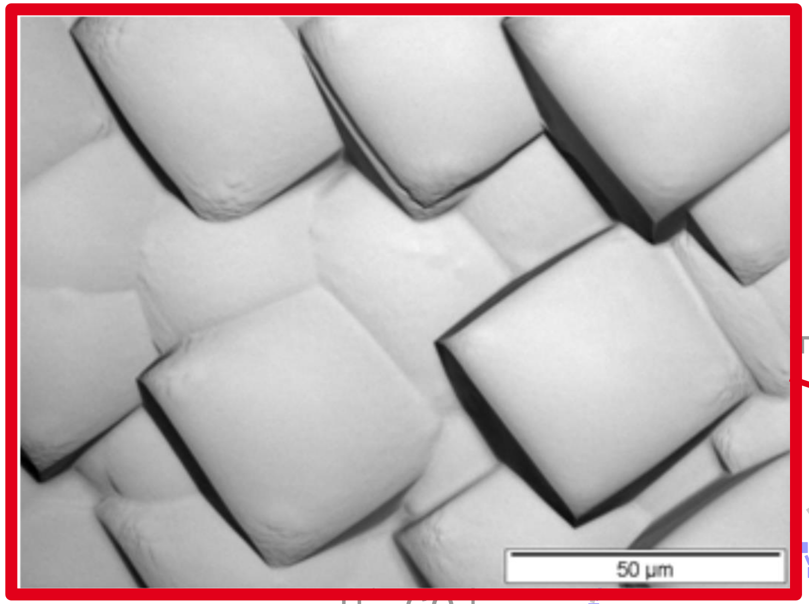
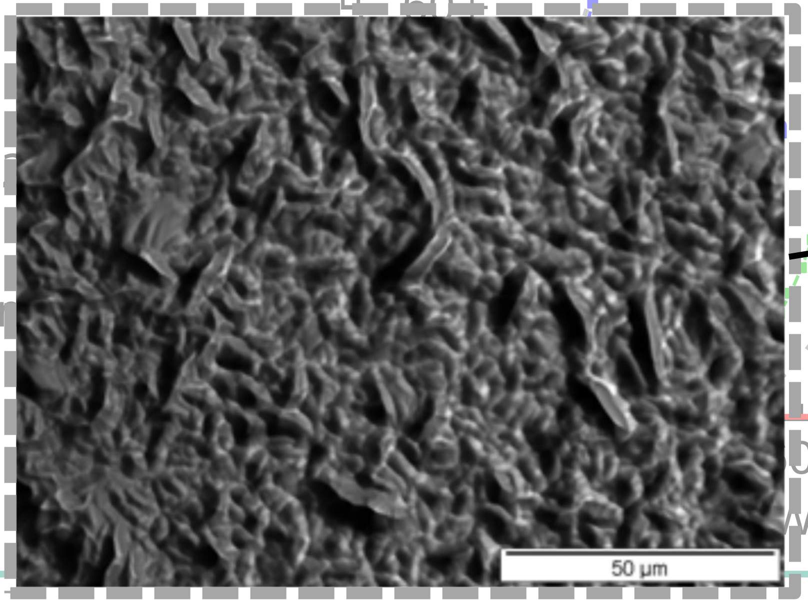
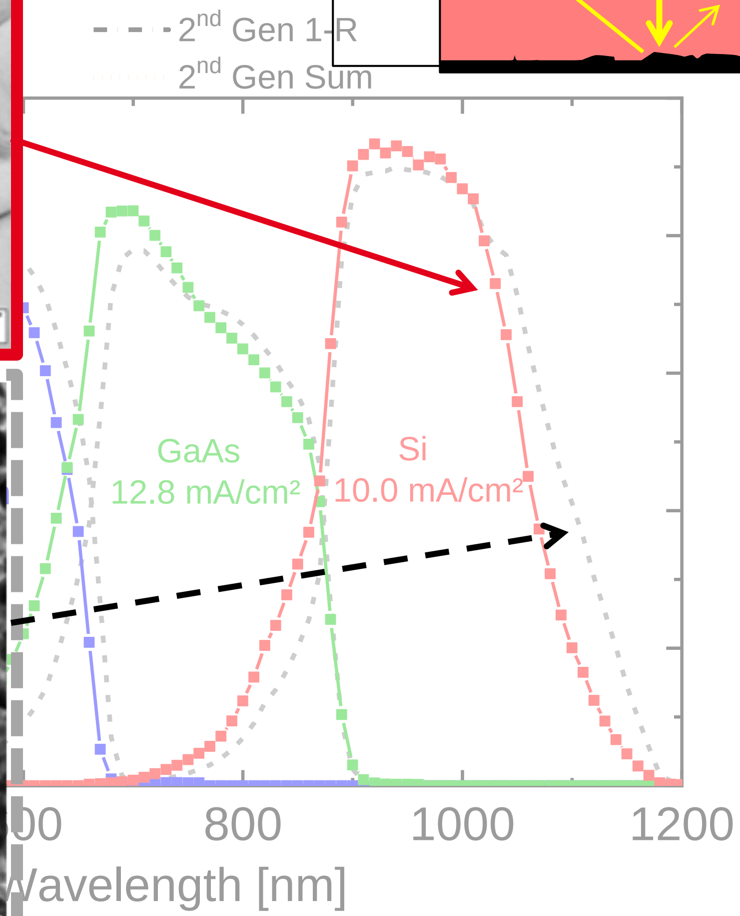
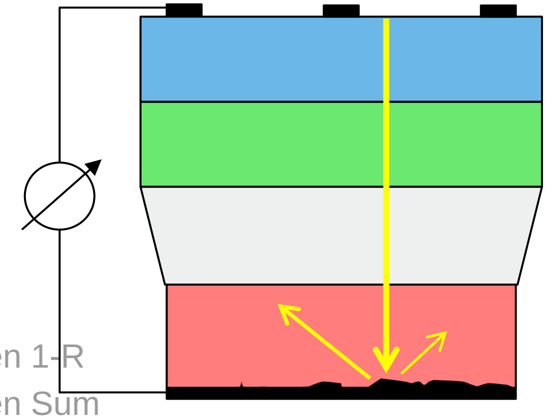
Si back side texture









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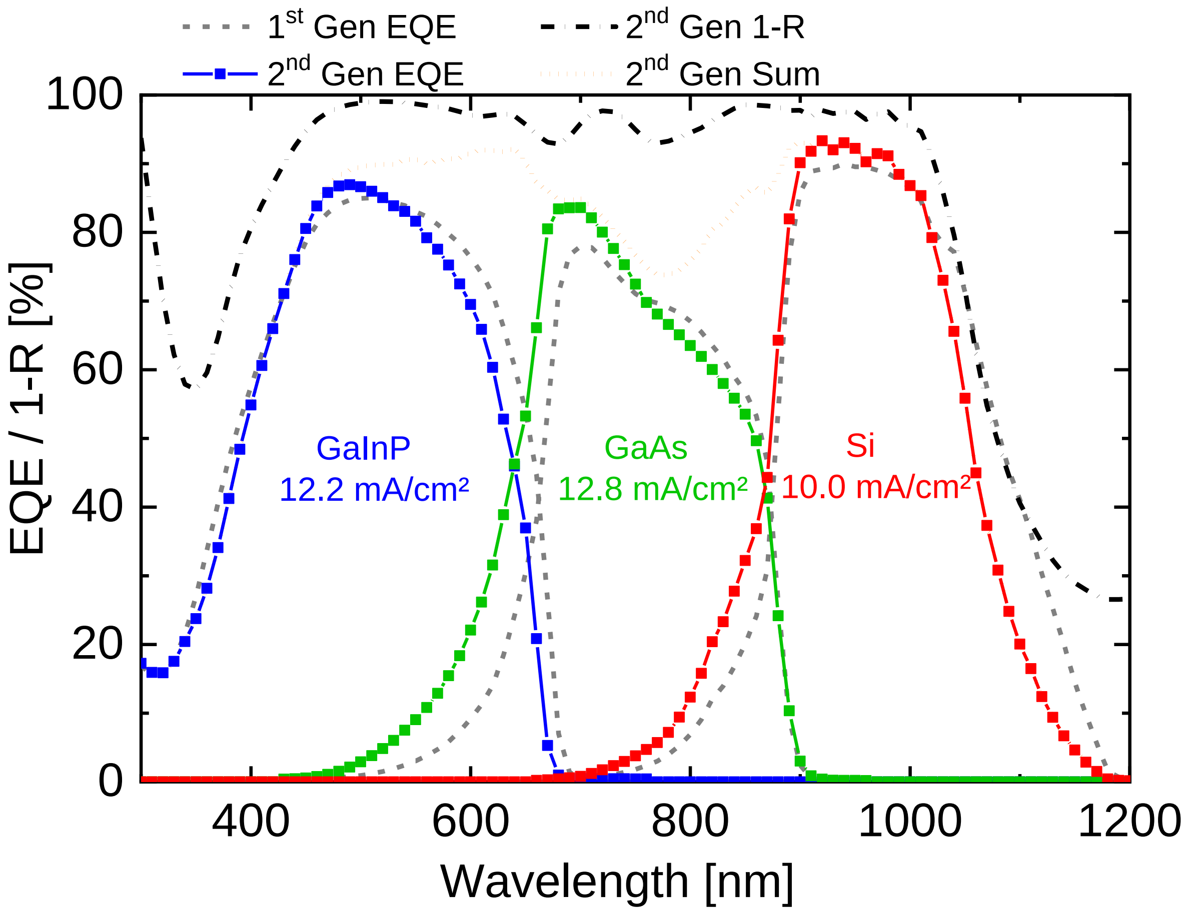
  - Poor light trapping in Si bottom cell
  - Strong parasitic absorption in GaAsP buffer for 700nm < λ < 900 nm



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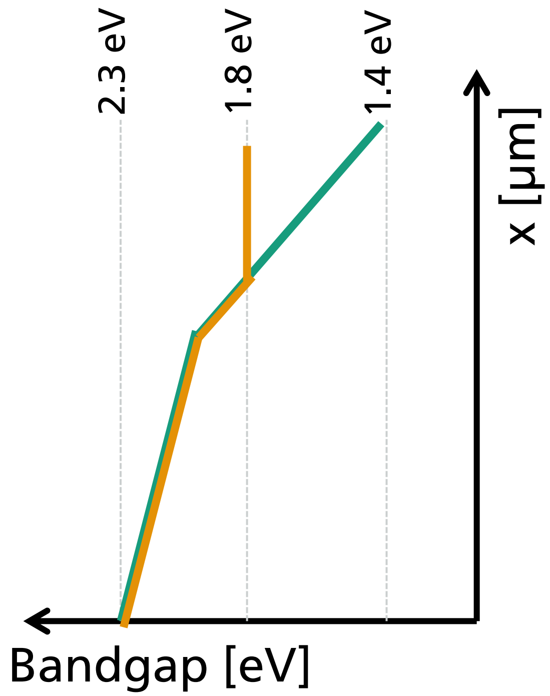
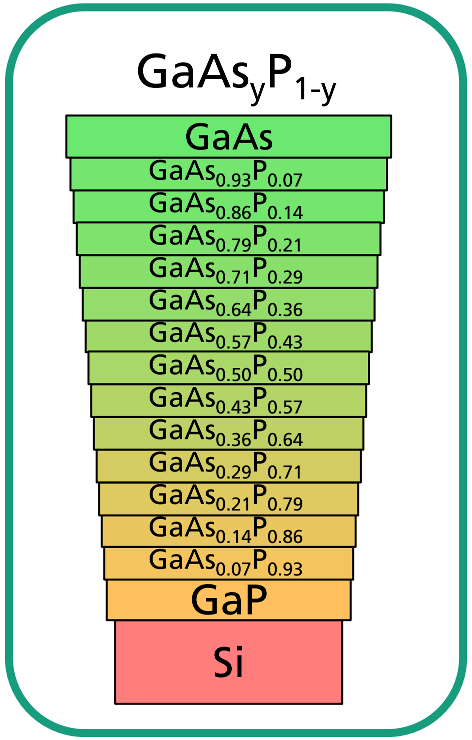
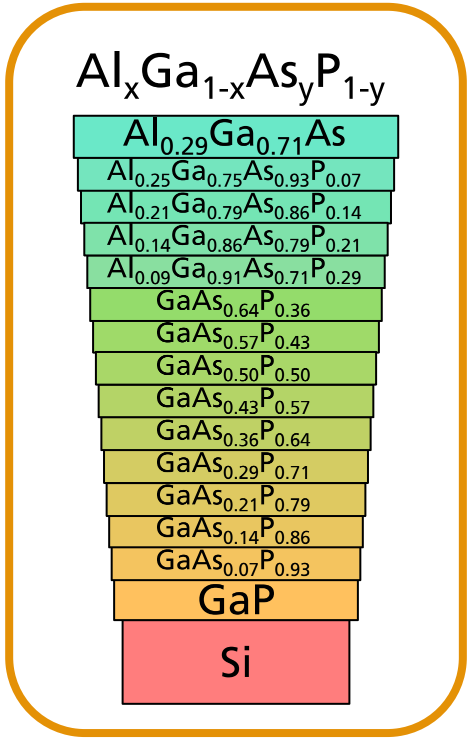
2nd Gen III-V on Si Solar Cell

Parasitic Absorption

- Increase bandgap of buffer layers to $E_g \geq 1.8$ eV ≡ 690 nm
- $Al_{0.29}Ga_{0.71}As$ as last buffer layer

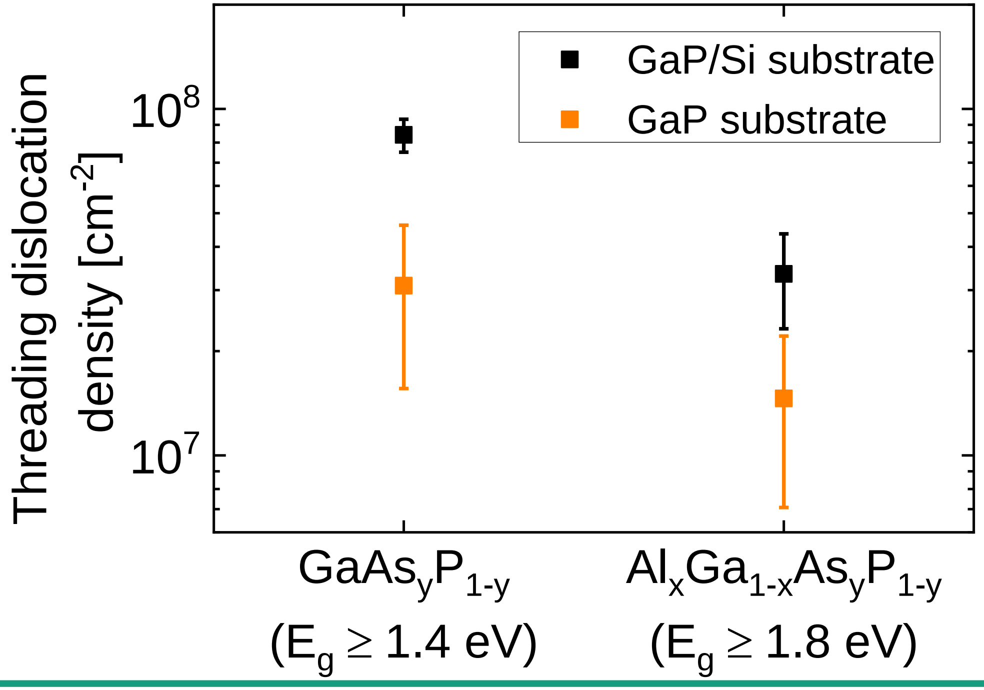


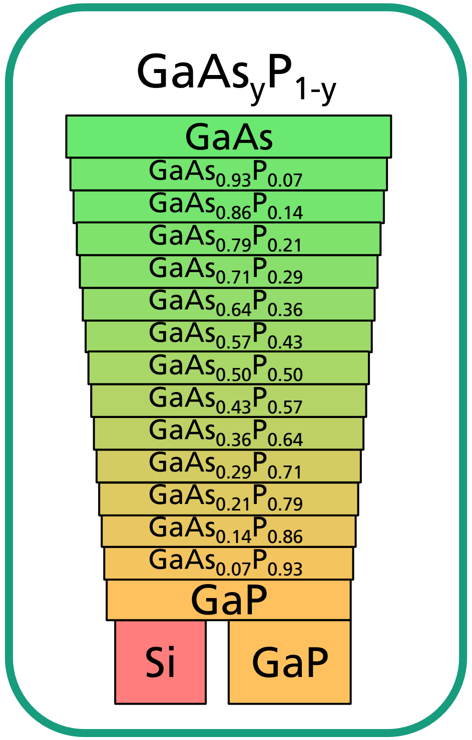


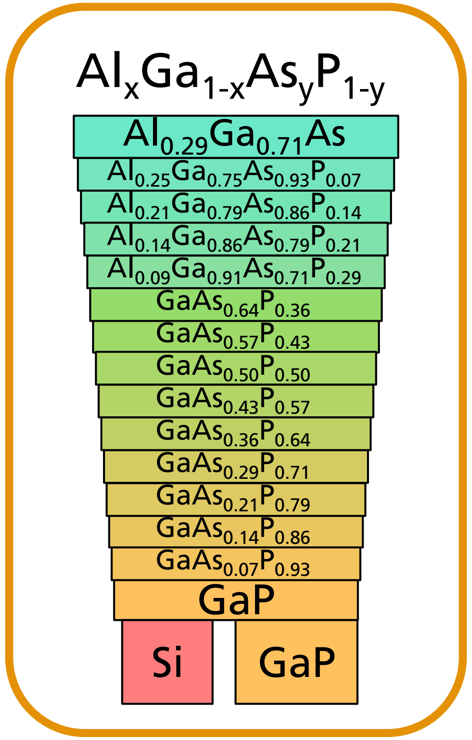


2^{nd} Gen III-V on Si Solar Cell
Parasitic Absorption

- Increase bandgap of buffer layers to $E_g \geq 1.8$ eV ≡ 690 nm
- $Al_{0.29}Ga_{0.71}As$ as last buffer layer
- Decreased threading dislocation density







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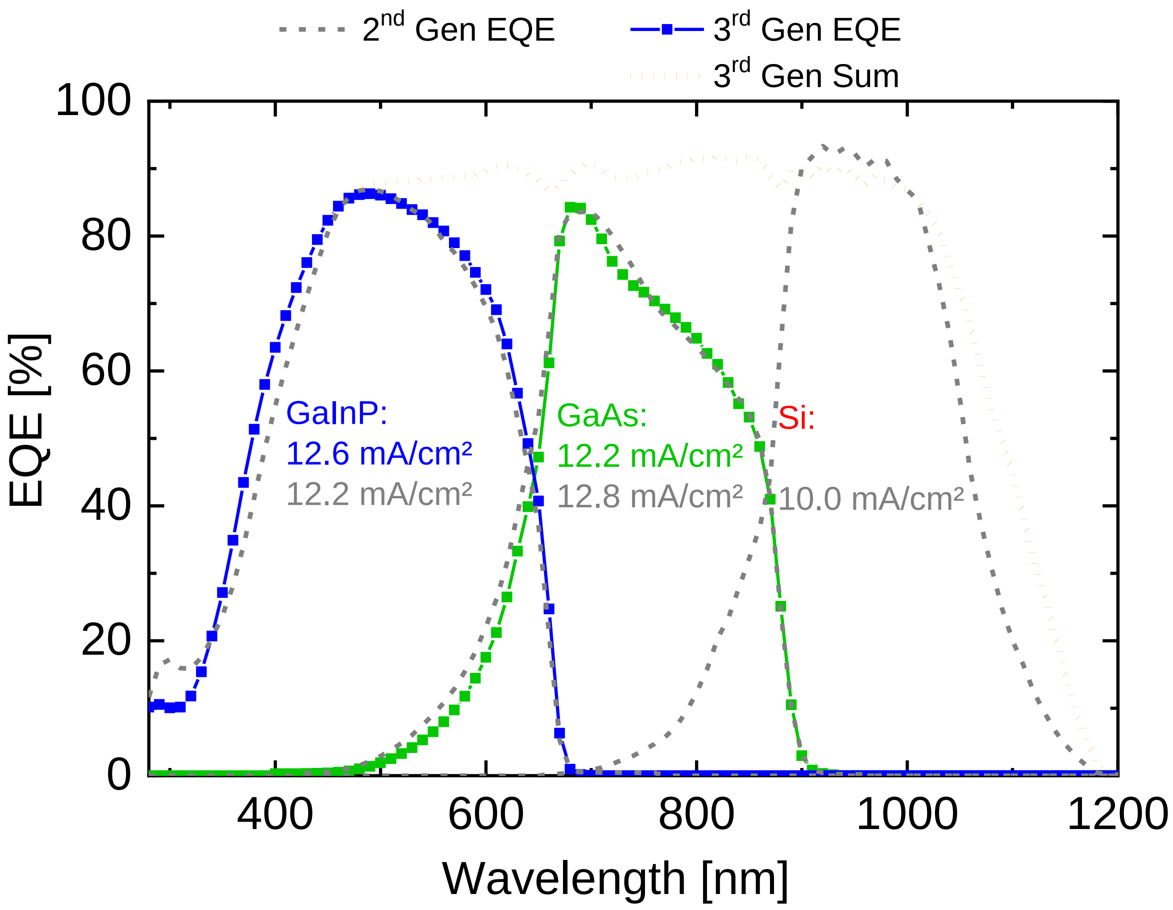
3rd Gen III-V on Si Solar Cell (2019)

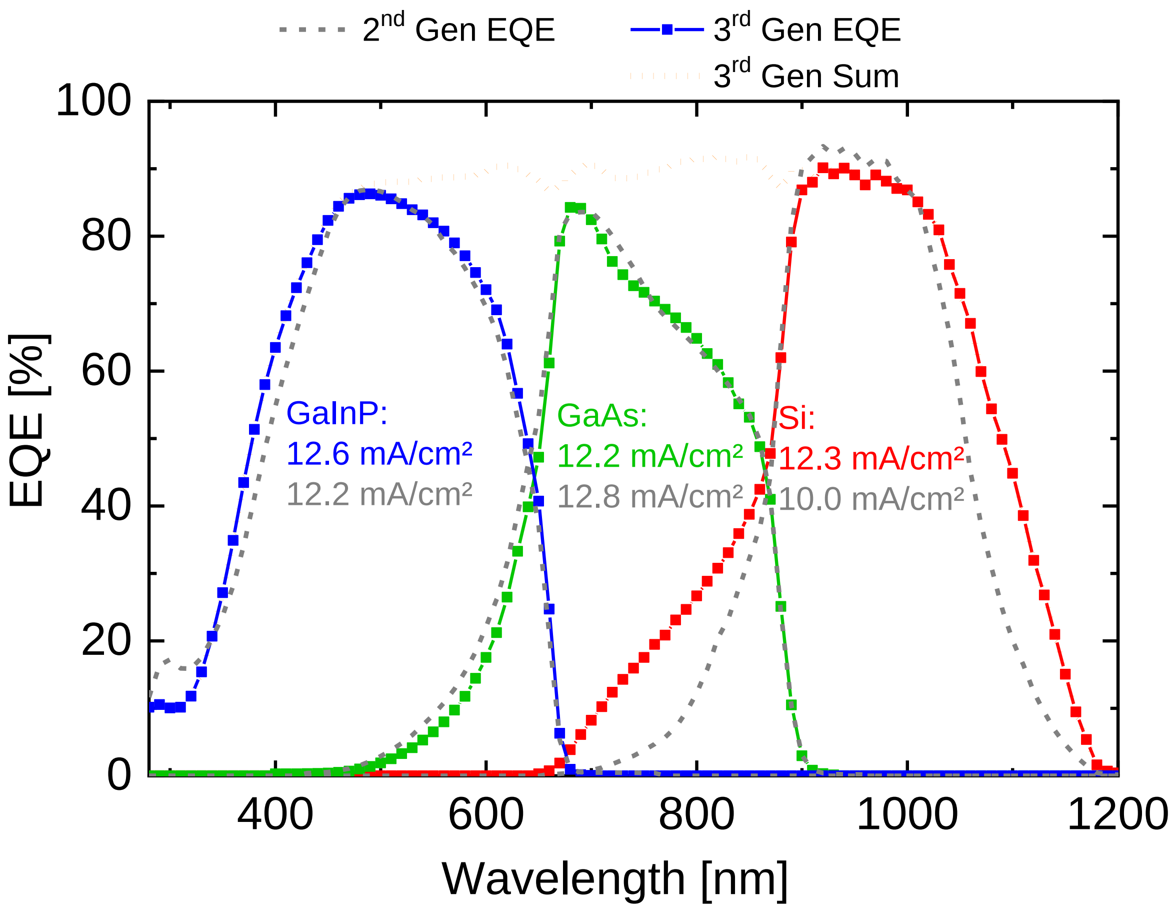
EQE

- EQE:
  - No significant change for GaInP and GaAs subcells



3^{rd} Gen III-V on Si Solar Cell
EQE

- EQE:
  - No significant change for GaInP and GaAs subcells
  - Improved/recovered light trapping
  - No significant parasitic absorption
  - +2.3 mA/cm² increase for Si subcell



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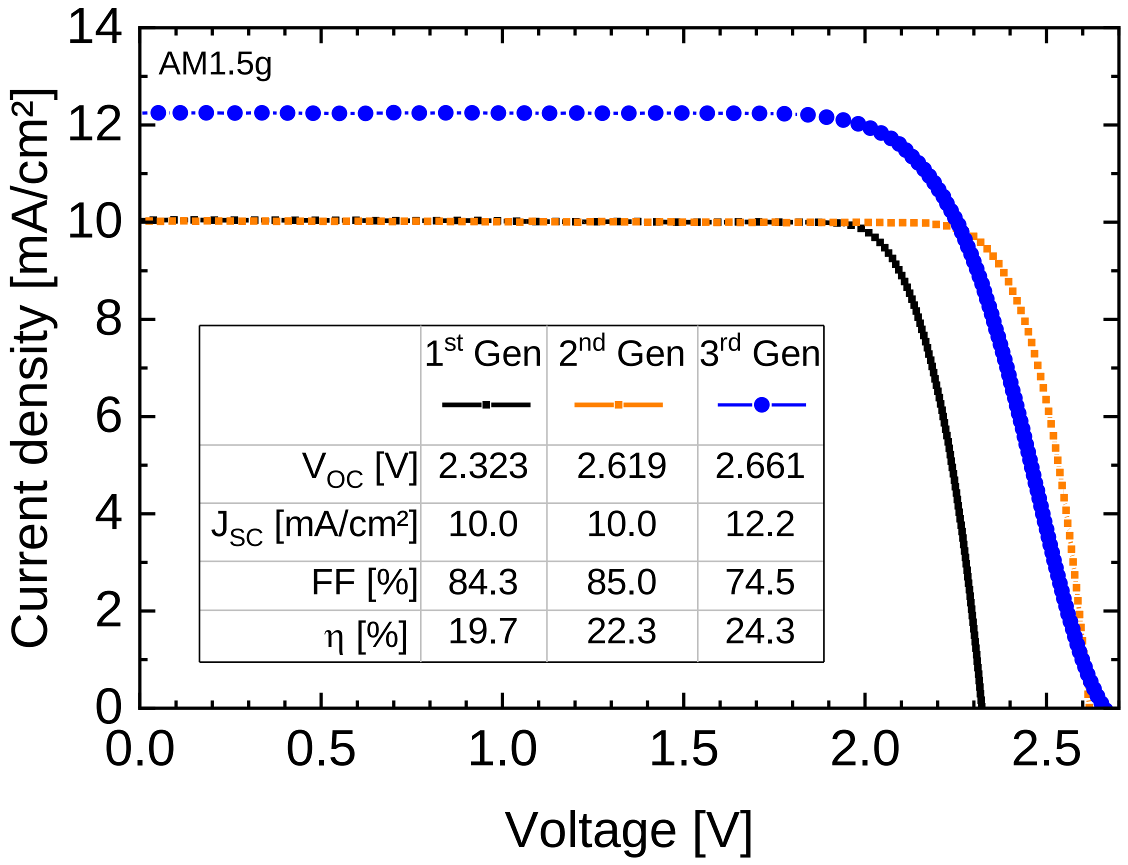
3rd Gen III-V on Si Solar Cell
IV-Characteristics

- EQE:
  - No significant change for GaInP and GaAs subcells
  - Improved/recovered light trapping
  - No significant parasitic absorption
  - +2.3 mA/cm² increase for Si subcell
- IV:
  - Lower TDD leads to increased V_{OC}
  - +2.2 mA/cm² gain in current
  - 24.3 % efficiency under AM1.5g (4 cm²)
  - Close to V_{OC} carrier transport issue occurs



	1st Gen	2nd Gen	3rd Gen
V_{OC} [V]	2.323	2.619	2.661
J_{SC} [mA/cm²]	10.0	10.0	12.2
FF [%]	84.3	85.0	74.5
η [%]	19.7	22.3	24.3

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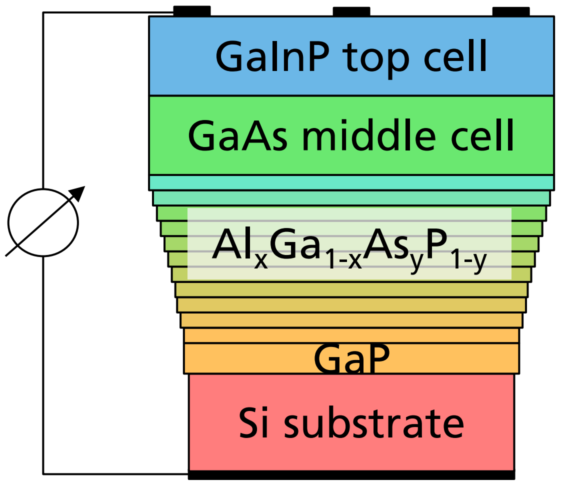
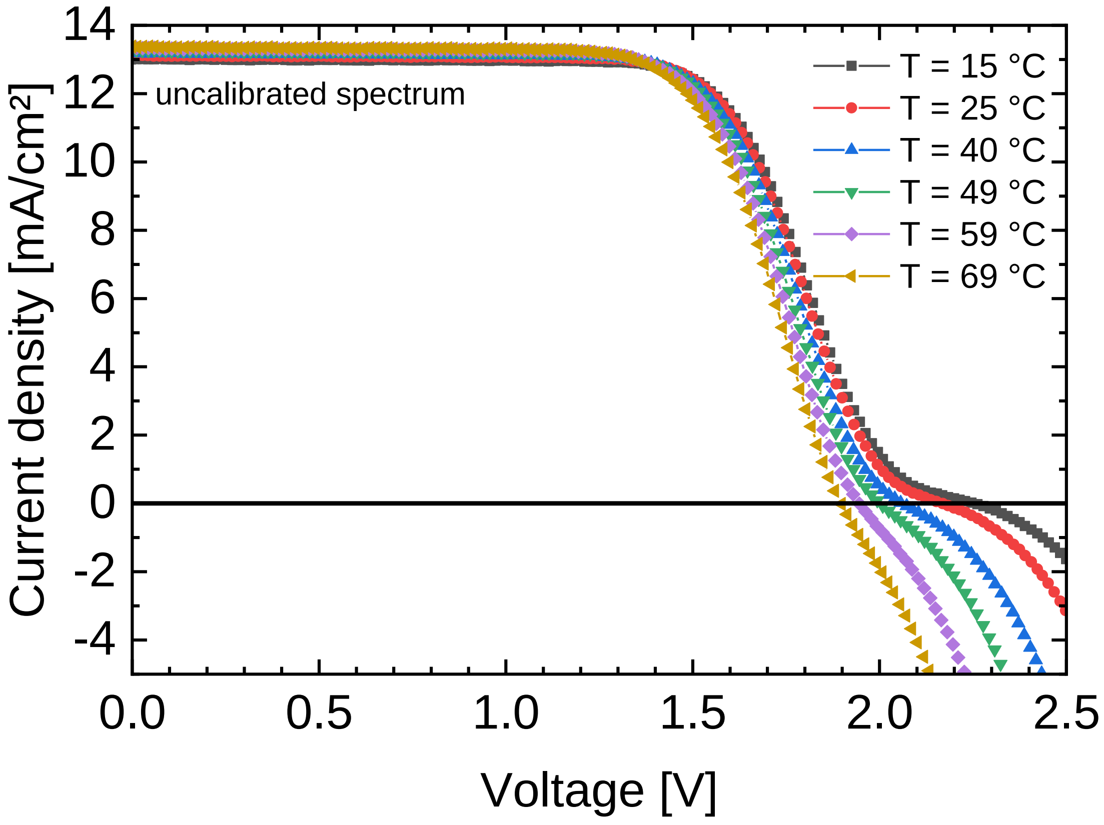
3^{rd} Gen III-V on Si Solar Cell
Temperature dependent IV

- S-shape in IV-characteristics
- Strong dependence on cell temperature
  → Majority barrier
- Barrier height[1)] 280 meV





1): Hoheisel et al., *IEEE Journal of Photovoltaics*, vol. 3, no. 2, p. 398, 2012

3^{rd} Gen III-V on Si Solar Cell

Temperature dependent IV

- S-shape in IV-characteristics
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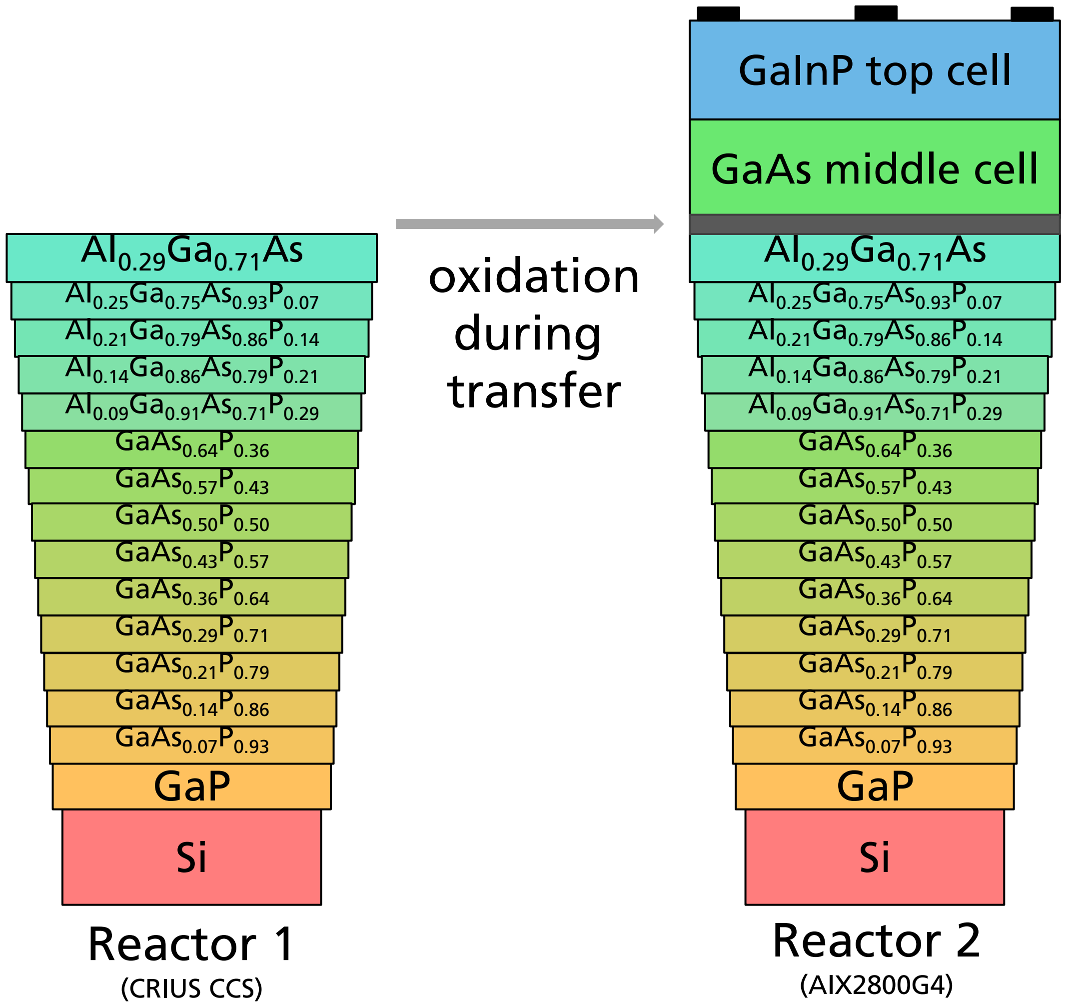
- 2-step MOVPE process
  - Oxidation of $Al_{0.3}Ga_{0.7}As$ layer during transfer causes barrier



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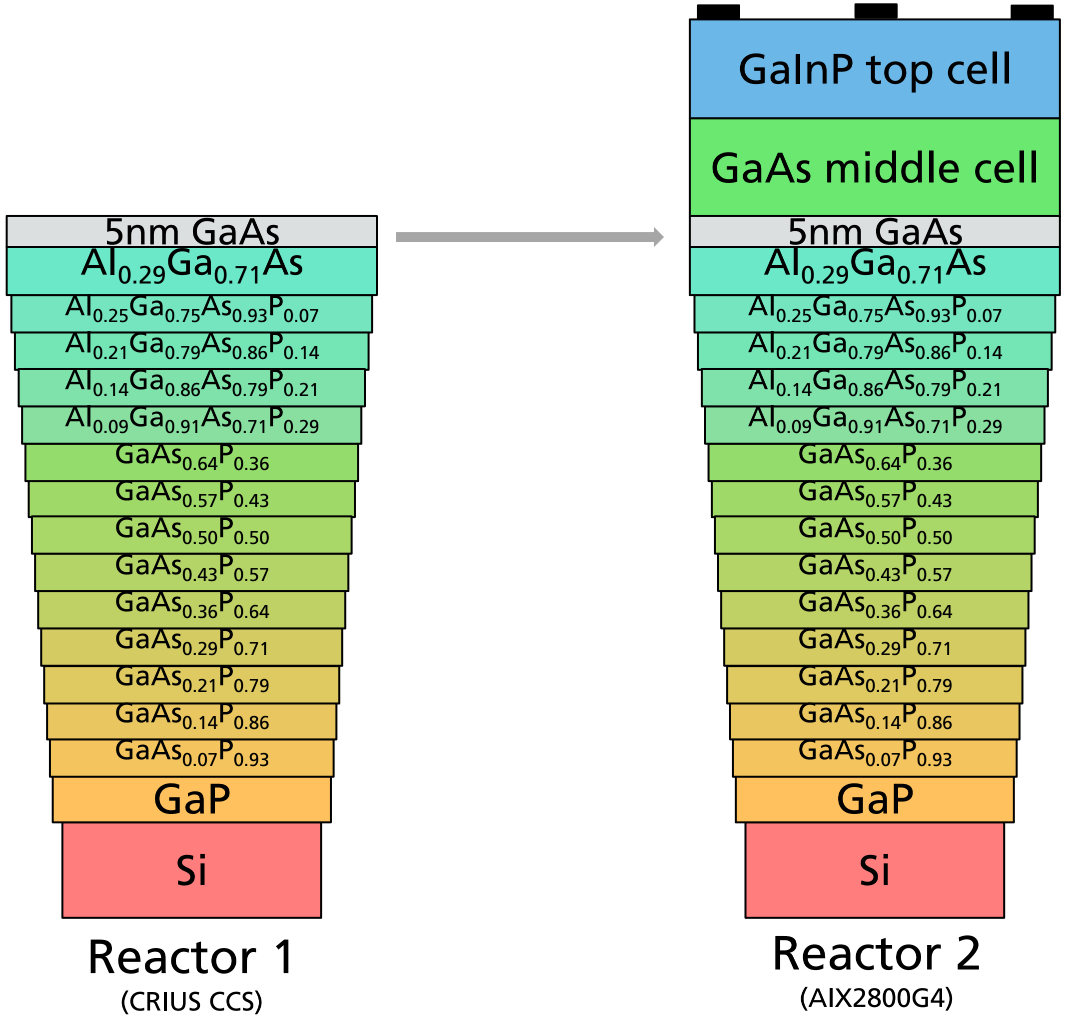
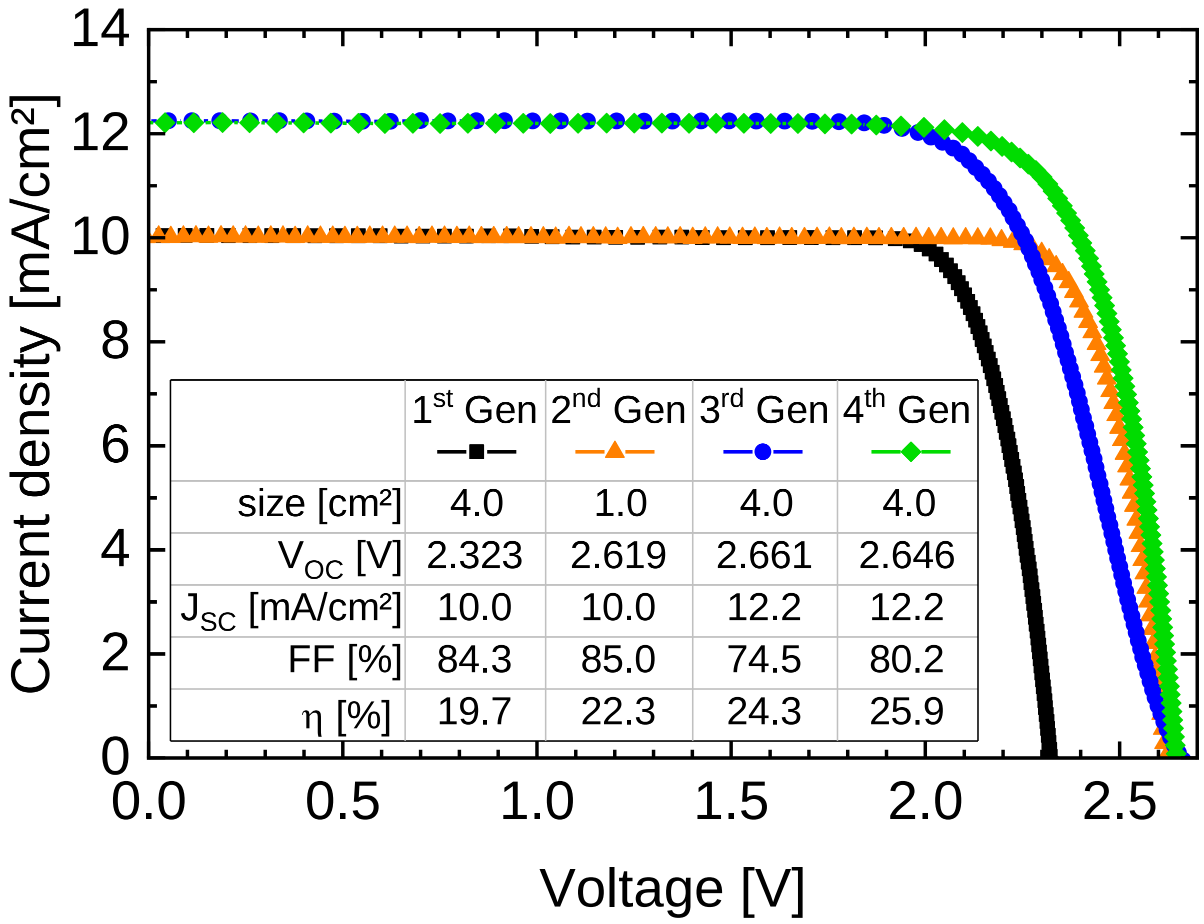
  - 5 nm GaAs cap to suppress oxidation



4th Gen III-V on Si Solar Cell (2020)

IV-Characteristics

- IV:
  - No sign of majority barrier
  - Fill factor increased to 80.2 %
  - **Record efficiency: 25.9 % @ AM1.5g[1)]**



	1st Gen	2nd Gen	3rd Gen	4th Gen
size [cm²]	4.0	1.0	4.0	4.0
V_{OC} [V]	2.323	2.619	2.661	2.646
J_{SC} [mA/cm²]	10.0	10.0	12.2	12.2
FF [%]	84.3	85.0	74.5	80.2
η [%]	19.7	22.3	24.3	25.9

1) Verified by Fraunhofer ISE CalLab

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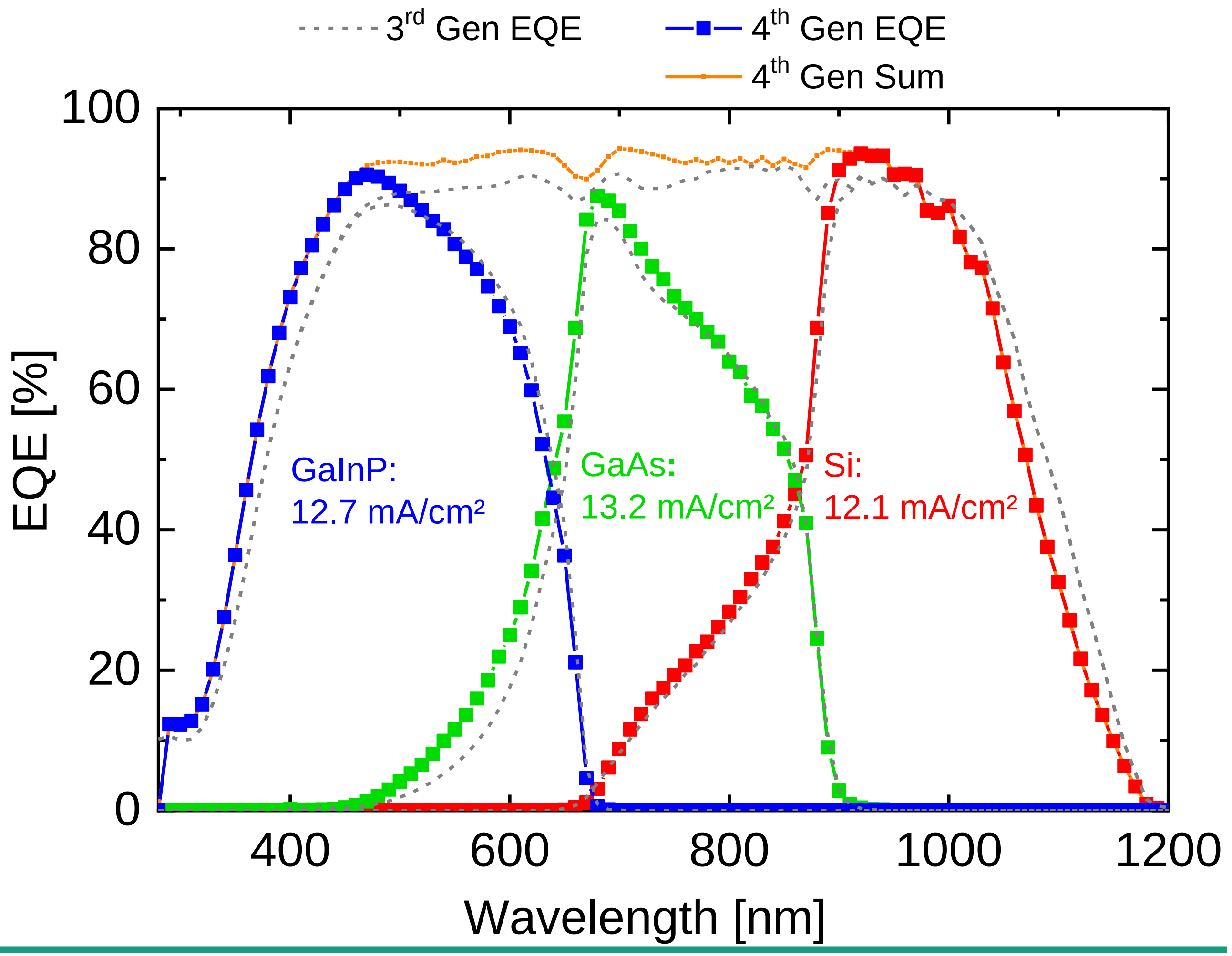
4th Gen III-V on Si Solar Cell

EQE

- IV:
  - No sign of majority barrier
  - Fill factor increased to 80.2 %
  - **Record efficiency: 25.9 % @ AM1.5g[1)]**
- EQE:
  - Increased EQE for GaAs and GaInP cell (structural changes in cell structure)[2)]
  - Current matching to be adjusted in future device

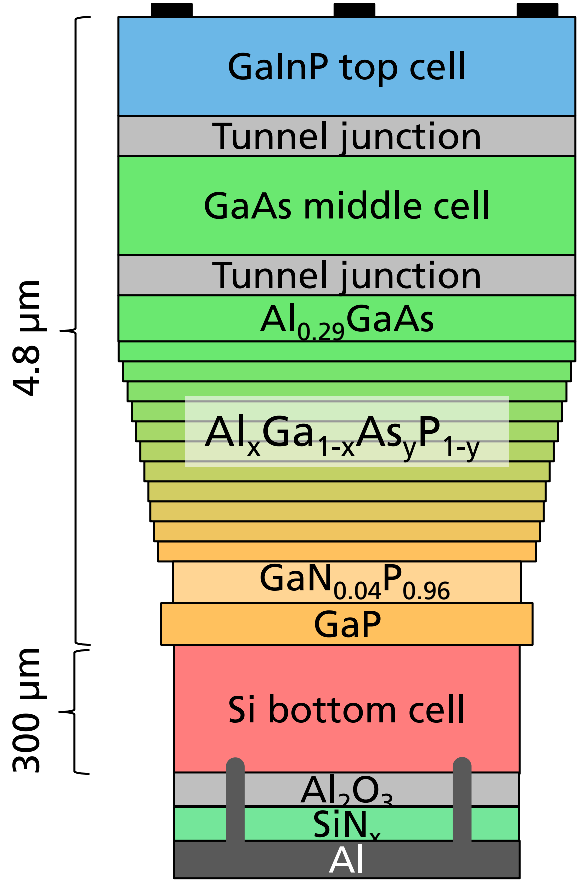


1) Verified by Fraunhofer ISE CalLab
2) Details in upcoming publication

Summary

- MOVPE-growth of GaInP/GaAs/Si triple junction solar cells
- **Certified 25.9 % conversion efficiency** @ AM1.5g for 4 cm² cell

- Rapid efficiency improvement from 19.7 % (2017) to 25.9 % (2020)
  - Stacking fault (pyramid) density in GaP on Si nucleation layer reduced from 6×10^7 cm^{-2} to $<10^5$ cm^{-2}
  - Parasitic absorption in $GaAs_yP_{1-y}$ buffer structure suppressed by using $Al_xGa_{1-x}As_yP_{1-y}$



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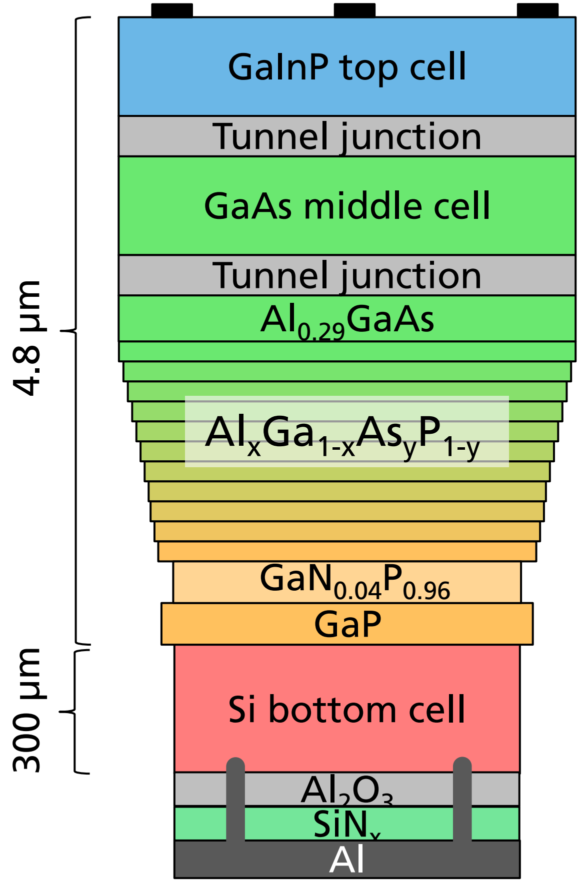
- **Outlook:**
  - Record cell is grown on low-cost Si surface finish (no CMP) TOPSIL



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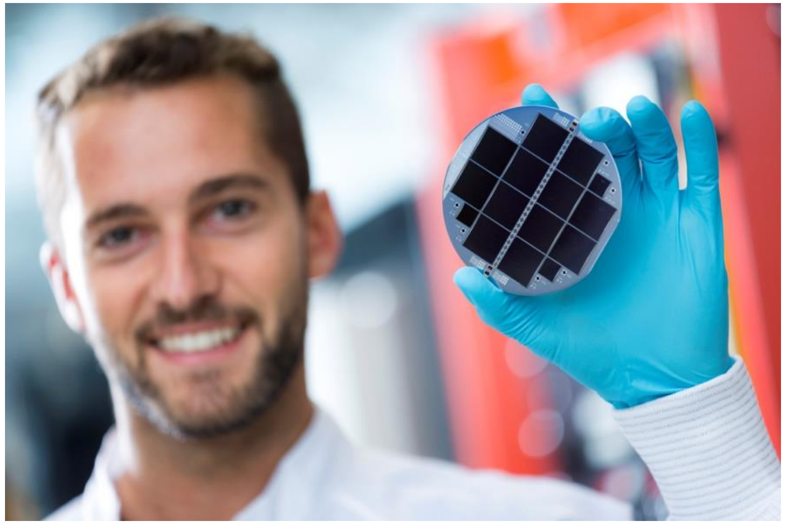
Thank you for listening!



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