Triple-junction InGaP/GaAs//InGaAs Solar cell for Mobile Devices

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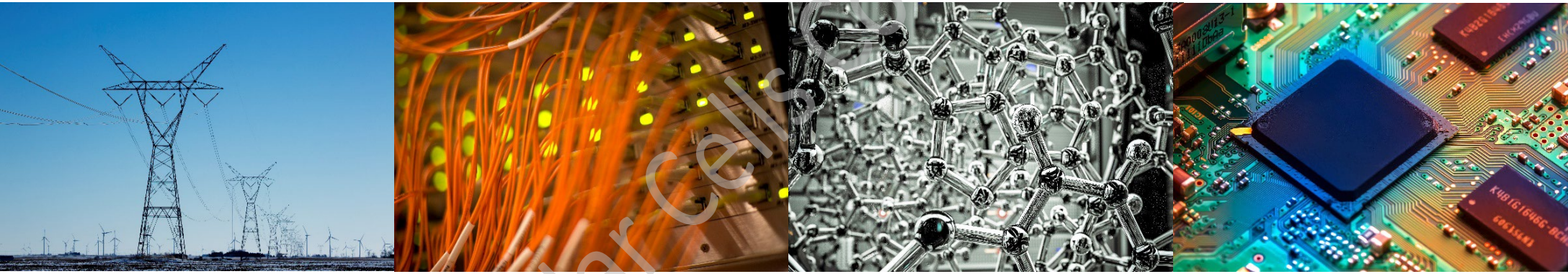
ECE 443 Final Project



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Motivation

- Widespread dependence on mobile devices
  - Emergency services
  - Navigation
- Limited surface area
  - Silicon: η ~ 20% [1]
  - InGaP/GaAs/Ge: η ~ 32% [2]
  - InGaP/GaAs/InGaAs: η ~ 34% [3]
- Decrease cost
  - Mechanically bonded InGaP/GaAs to InGaAs cell
  - No buffer region needed

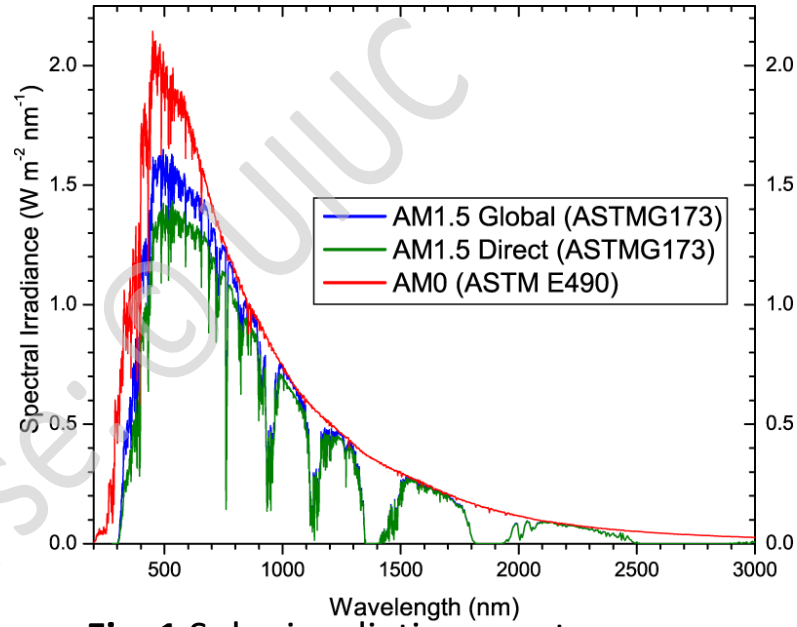


Fig. 1 Solar irradiation spectrums (AM1.5G in Green) [4]

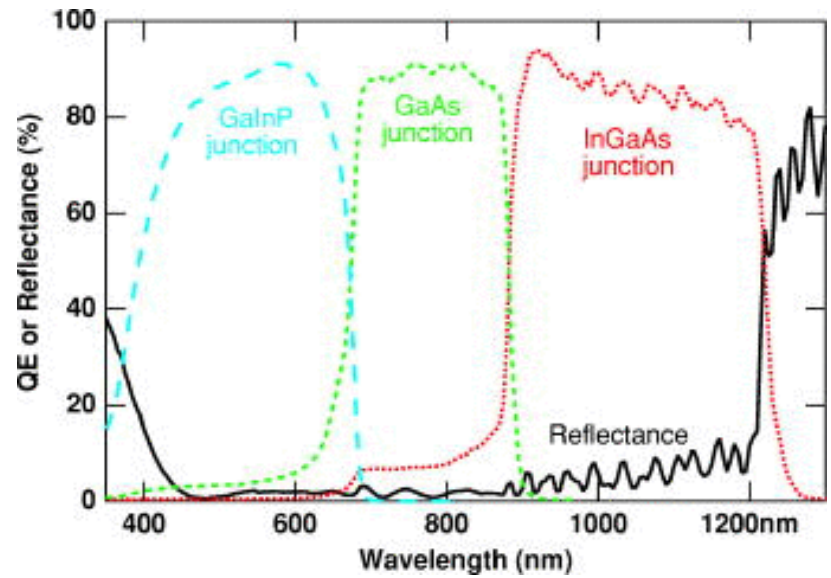


Fig. 2 QE of InGaP/GaAs/InGaAs structure [5]

[1] Solar Technologies Office, "Crystalline Silicon Photovoltaics Research," Office of Energy Efficiency and Renewable Energy, [Online].
[2] D. Aiken, Conference Record of the Twenty-Eighth IEEE Photovoltaic Specialists pp. 994-997, 2000.
[3] T. Takamoto, et.al. 2010 35th IEEE Photovoltaic Specialists Conference, pp. 412-417, 2010.
[4] C. Honsberg and S. Bowden, "Standard Solar Spectra," ASTM G-173-03. [Online].
[5] J. Geisz et.al. Appl. Phys. Lett., vol. 91, no. 023502, 2007

Background

- Current Matching
  - InGaP/GaAs/Ge: too much bottom cell current
  - InGaP/GaAs/InGaAs: larger bandgap = larger V_{OC}
- Lattice Matching
  - a_{GaAs} = 5.65 Å; a_{InGaAs} = 5.77 Å % → Difference: 2.1%
  - Strained structures: altered band structure
  - Misfit dislocations: recombination sites

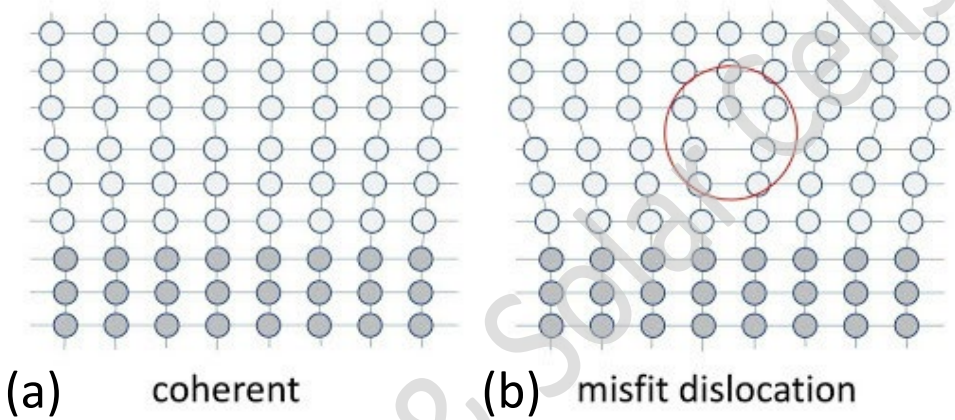


Fig. 3a Lattice-matched semiconductor
Fig. 3b Lattice mismatch leading to a misfit dislocation [6]

- Graded buffer: extra fabrication, extra expense
- Mechanical bonding: transparent layers between cells

[6] J. J. Coleman, "Strained semiconductor layers shift the paradigm," EE Times Asia, 17-Jun-2021. [Online].

Device Structure

InGaP Window	n-$In_{0.5}Al_{0.5}P$	d=0.02 um	2e18 cm^{-3}
InGaP Emitter	n-$In_{0.51}Ga_{0.49}P$	d=0.1 um	2e18 cm^{-3}
InGaP Base	p-$In_{0.51}Ga_{0.49}P$	d=0.9 um	1.5e17 cm^{-3}
InGaP BSF	p-$In_{0.5}Ga_{0.25}Al_{0.25}P$	d=0.05 um	1.5e17 cm^{-3}
Tunnel Junction	p-$Al_{0.3}Ga_{0.7}As$	d=0.01 um	5e19 cm^{-3}
Tunnel Junction	n-$In_{0.51}Ga_{0.49}P$	d=0.01 um	2e19 cm^{-3}
GaAs Window	n-$In_{0.51}Ga_{0.49}P$	d=0.05 um	2e18 cm^{-3}
GaAs Emitter	n-GaAs	d=0.1 um	2e18 cm^{-3}
GaAs Base	p-GaAs	d=5 um	1e17 cm^{-3}
GaAs BSF	p-$In_{0.51}Ga_{0.49}P$	d=0.07 um	2e18 cm^{-3}

(a)

InGaP Top Cell (E_g=1.86 eV)

Tunnel Junctions

GaAs Top Cell (E_g=1.39 eV)

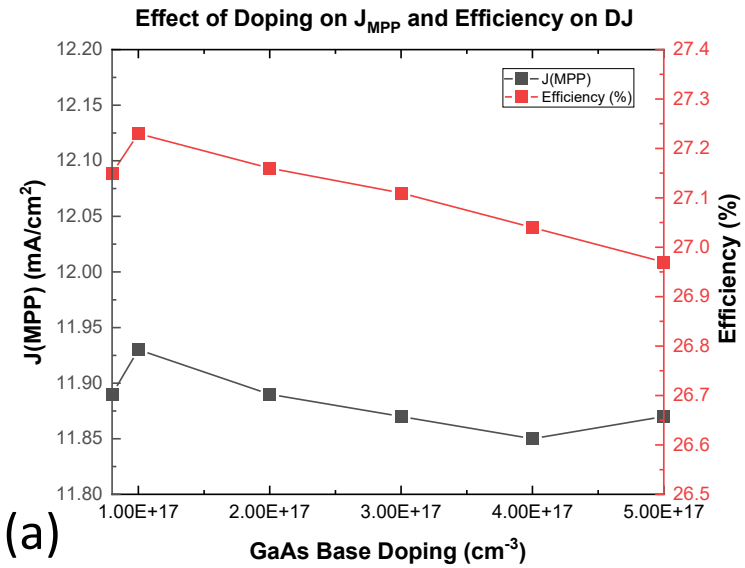
(b)

InGaAs Window	n-$In_{0.3}Ga_{0.7}As$	d=0.05	2e18 cm^{-3}
InGaAs Emitter	n-$In_{0.3}Ga_{0.7}As$	d=0.1um	5e18 cm^{-3}
InGaAs Base	p-$In_{0.3}Ga_{0.7}As$	d=1.75um	1e18 cm^{-3}

Fig. 4a Structure of optimized dual junction InGaP/GaAs cell with layer functionality, composition, thickness, and doping levels (left)
Fig. 4b Structure of optimized single junction InGaAs cell (top)

- Window: prevent electrons from recombining at front surface
- BSF: prevent holes from recombining at back surface
- Tunnel junction: enable tunneling between cells without reverse current (reverse pn junction)

Parameter Optimization



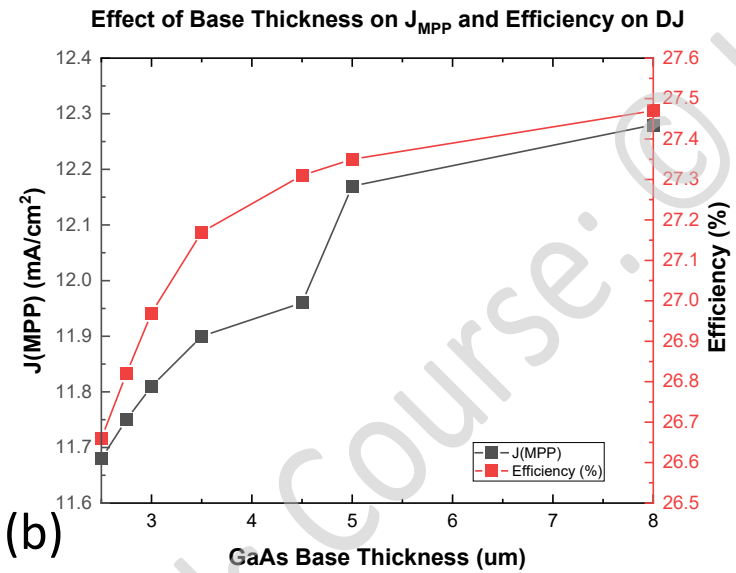
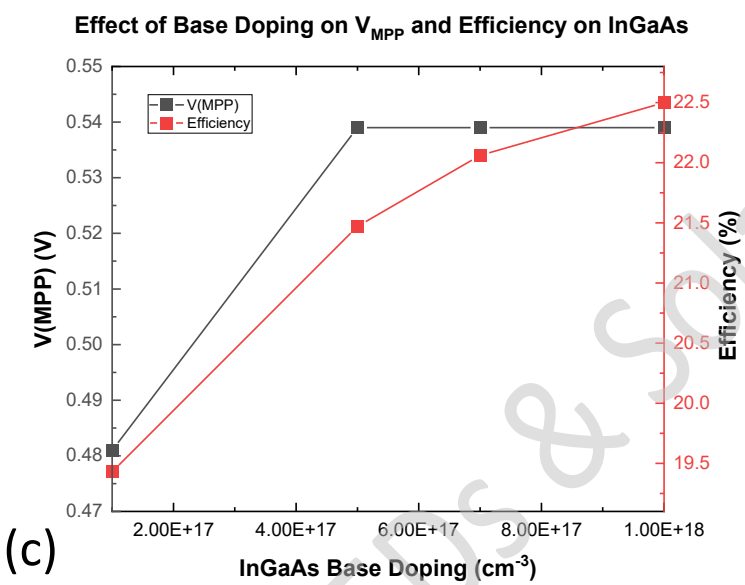


Fig. 5a Effect of GaAs base doping concentration on J_{MPP} and efficiency
Fig. 5b Effect of GaAs base thickness on J_{MPP} and efficiency



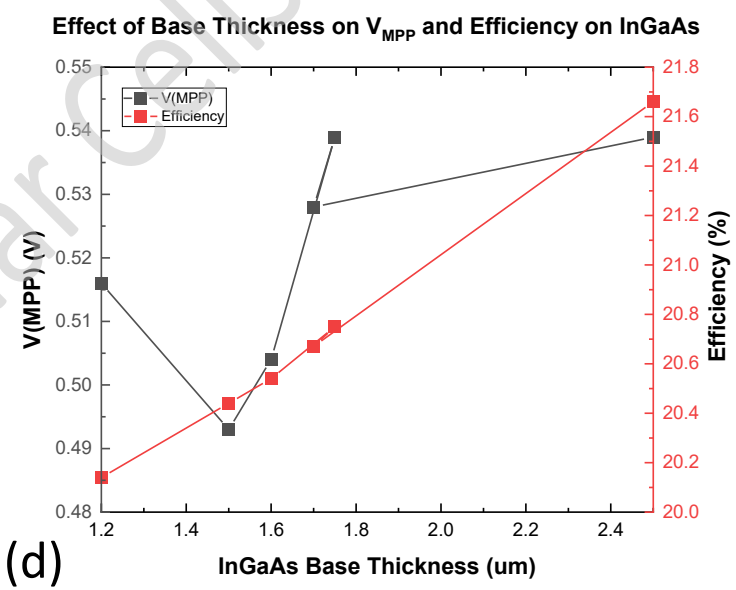
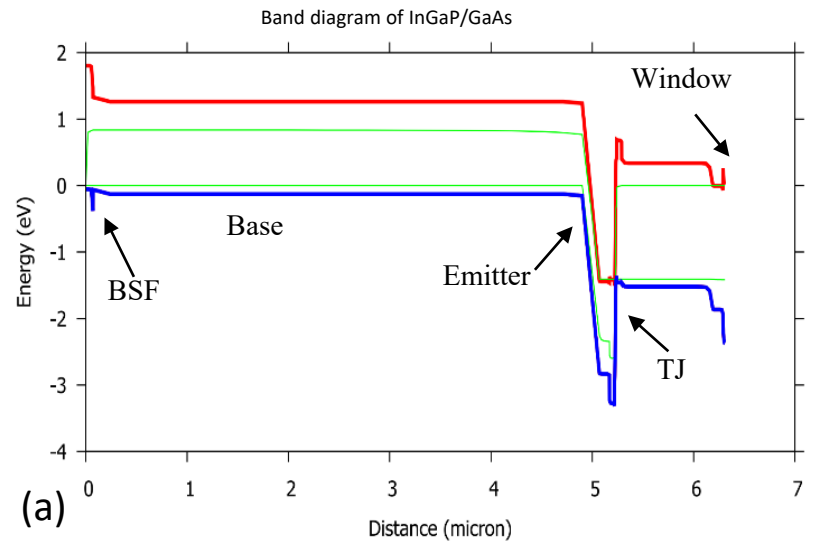


Fig. 5c Effect of InGaAs base doping concentration on J_{MPP} and efficiency
Fig. 5d Effect of InGaAs base thickness on J_{MPP} and efficiency

Simulated Results



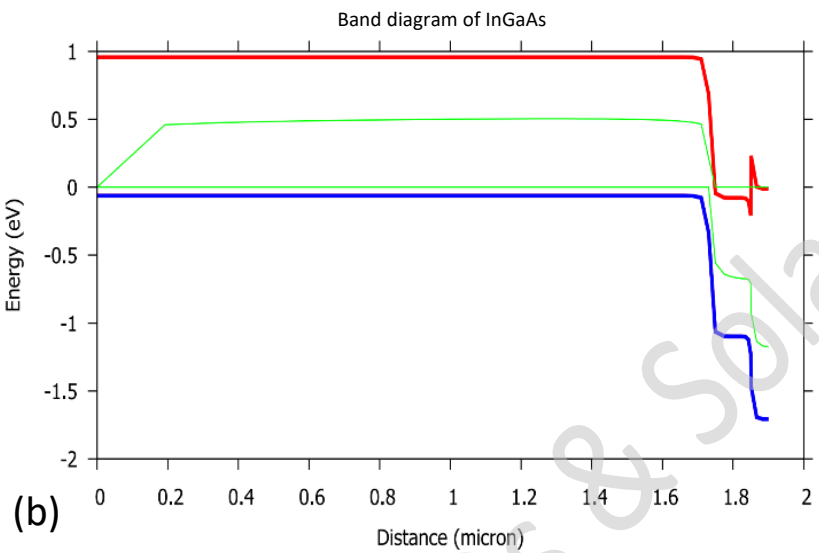
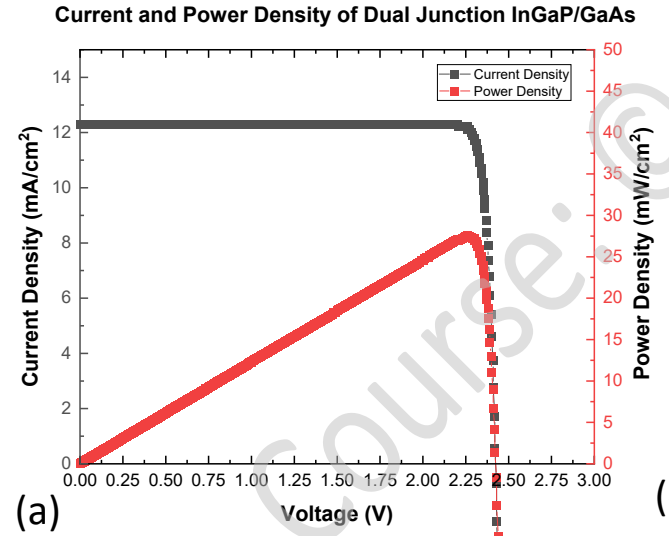
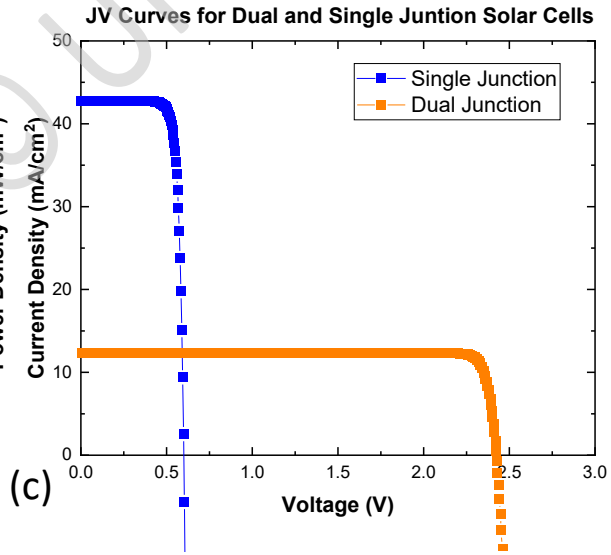
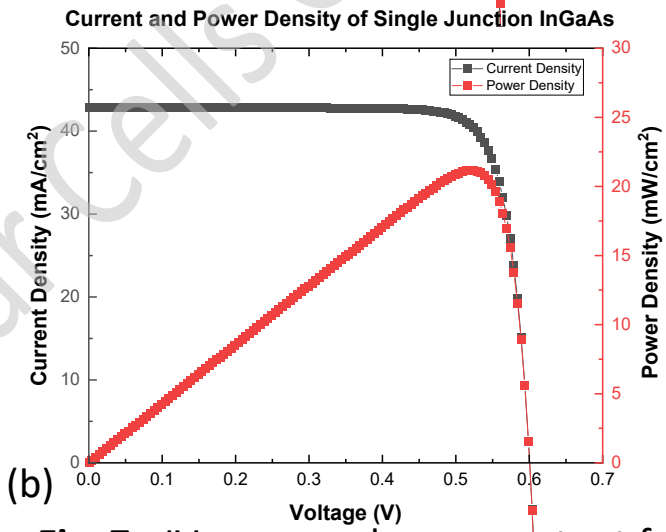


Fig. 6a Band diagram for InGaP/GaAs
Fig. 6b Band diagram for InGaAs







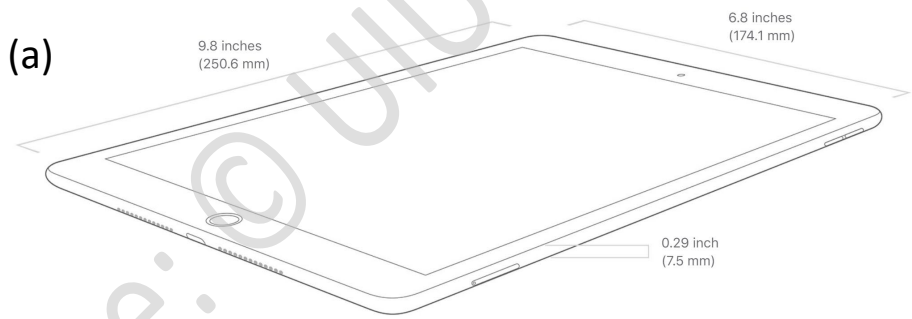
J_{MPP} = 12.17 mA/cm^2
V_{MPP} = 2.787 V
P_{MPP}= 14.8 W
η = 34%

Fig. 7a JV curve and power output for InGaP/GaAs
Fig. 7b JV curve and power output for InGaAs
Fig. 7c JV curves for InGaP/GaAs and InGaAs

Application and Next Steps

Financial Feasibility

- iPad 8th Gen: 5.2V; 2.4A [7]
  - Two cells in series: 5.57V; 2.65A [8]
  - $1031 at 200kW/yr production level [9]
- iPhone 13: 5V; 1A [7]
  - One iPhone-sized cell: 2.787V; 1.276A [10]
  - $250 at 200kW/yr production level [9]



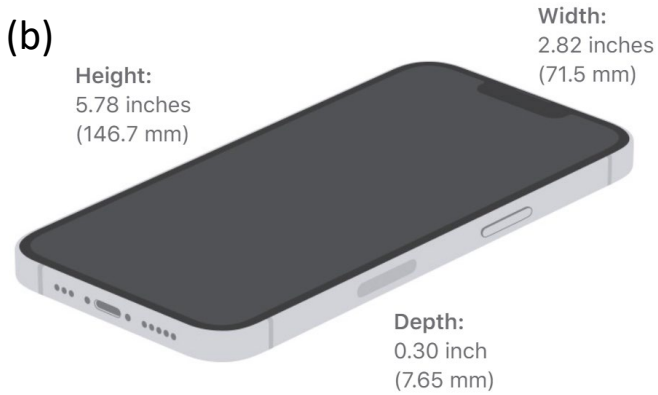


Fig. 8a iPad 8th Gen specs
Fig. 8b iPhone 13 pro specs

Next Steps

- MOCVD optimization for theoretical efficiencies
- Widespread adoption of technology: ↓ Cost

[7] Apple, "About Apple USB Power Adapters," Apple, [Online].
[8] Apple, "iPad Tech Specs," Apple, [Online].
[9] K. A. Horowitz, et.al. NREL, Golden, Colorado, rep., 2018.
[10] Apple, "iPhone 13 Tech Specs," Apple, [Online].

Conclusions

- Mobile devices: limited surface area
  - High efficiency: InGaP/GaAs//InGaAs
- Vary parameters
  - GaAs base thickness and doping
  - InGaAs base thickness and doping
  - Highest current density of GaAs
  - Highest voltage for InGaAs
  - J_{MPP} = 12.17 mA/cm^2; V_{MPP} = 2.787 V
- 34% efficient, good match to iPad charging
- Expensive: $1031 iPad/$250 iPhone