Hot carriers and phonon relaxation processes in InAs/AlAsSb quantum well solar cells

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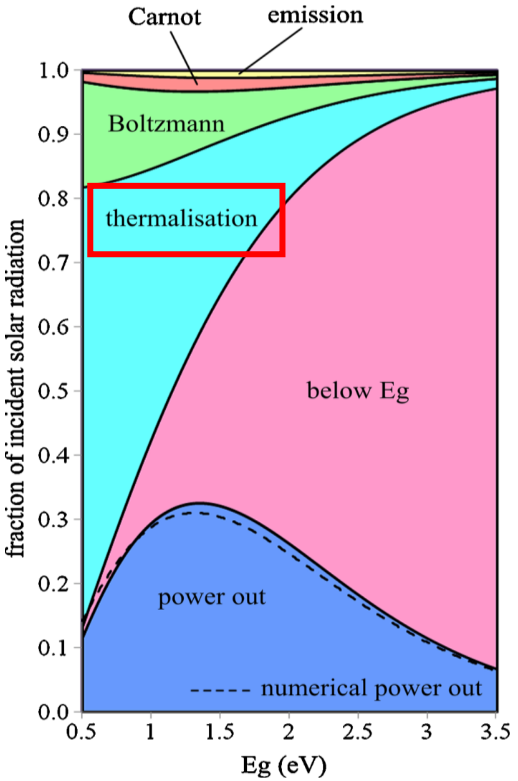
Outline

- Motivation
- Devices
- Simultaneous Photoluminescence/Current-Voltage Characterization
- Carrier Temperature vs. Device Performance
- Conclusions

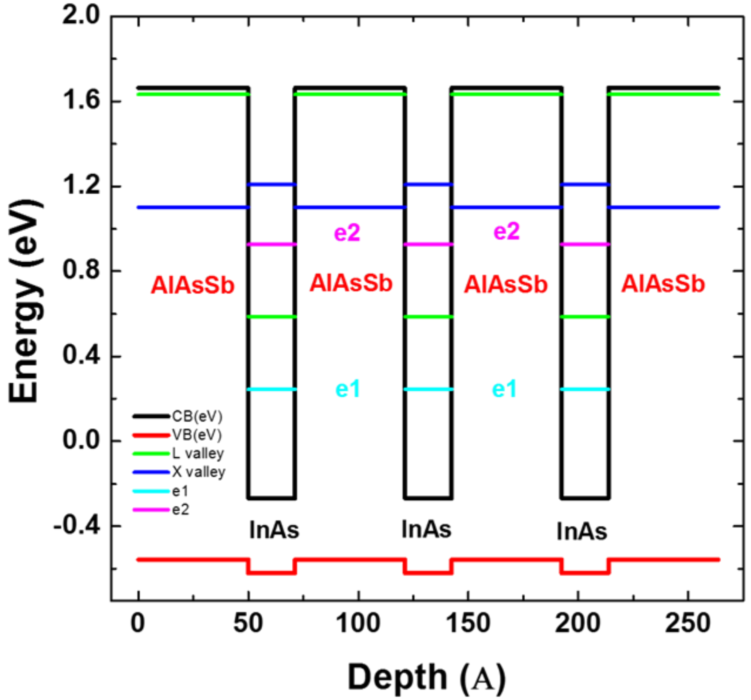
Motivation

- Quantum Well Solar Cells provide route to potentially harness hot carrier extraction
- InAs/AlAsSb: Type-II energy alignment and intervalley scattering provide path to long carrier lifetimes and a nonequilibrium carrier population
- "Deep" wells allow assessment of quantum well emission spectra far from other excited states, substrate, and barrier emission

L. C. Hirst, N. J. Ekins-Daukes, *Prog. PV* **2011**, 19, 286.



M. Lumb, *et al*, Vol. 8471, *SPIE*, **2012**

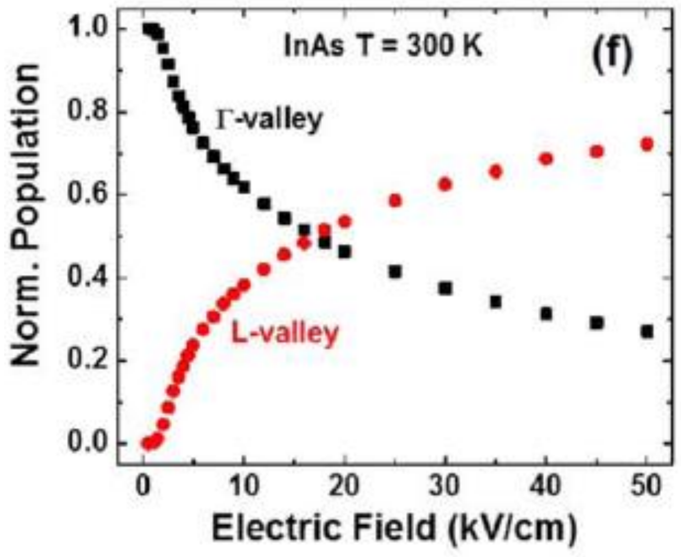


2.1 nm QW
5 nm Barrier

J. Tang, *et al*, *Applied Physics Letters* **2015**, 106, 061902
H. Esmaielpour, *et al*, *Progress in Photovoltaics: Research and Applications* **2016**, 24, 591
H. Esmaielpour, *et al*, *Scientific Reports* **2018**, 8, 12473
V. R. Whiteside, *et al*, *Semiconductor Science and Technology* **2019**, 34, 094001

Motivation

- Comprehensive study of barrier thickness/contribution



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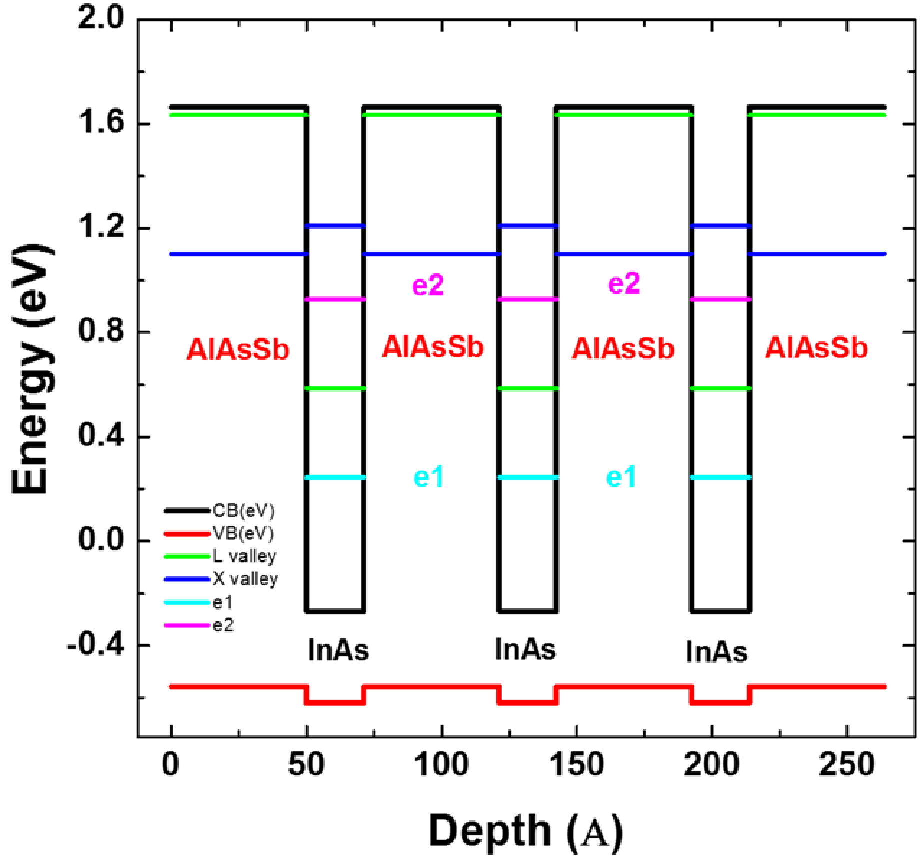
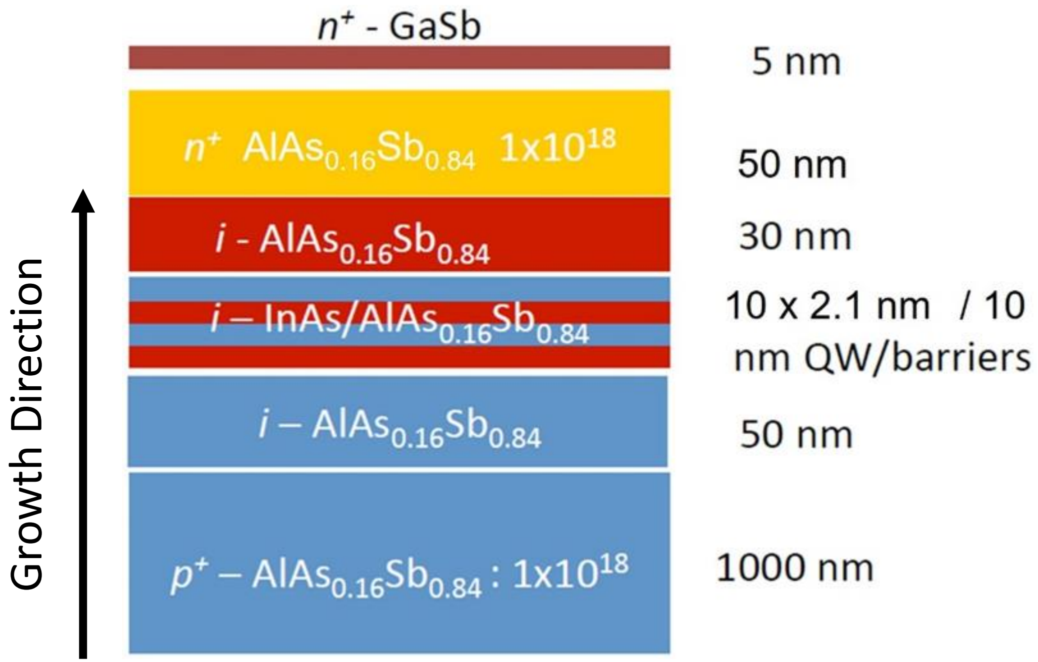


V. R. Whiteside, *et al*, *Semiconductor Science and Technology* **2019**, 34, 094001
H. Esmaielpour, *et al*, *Nature Energy* **2020**, 5, 336

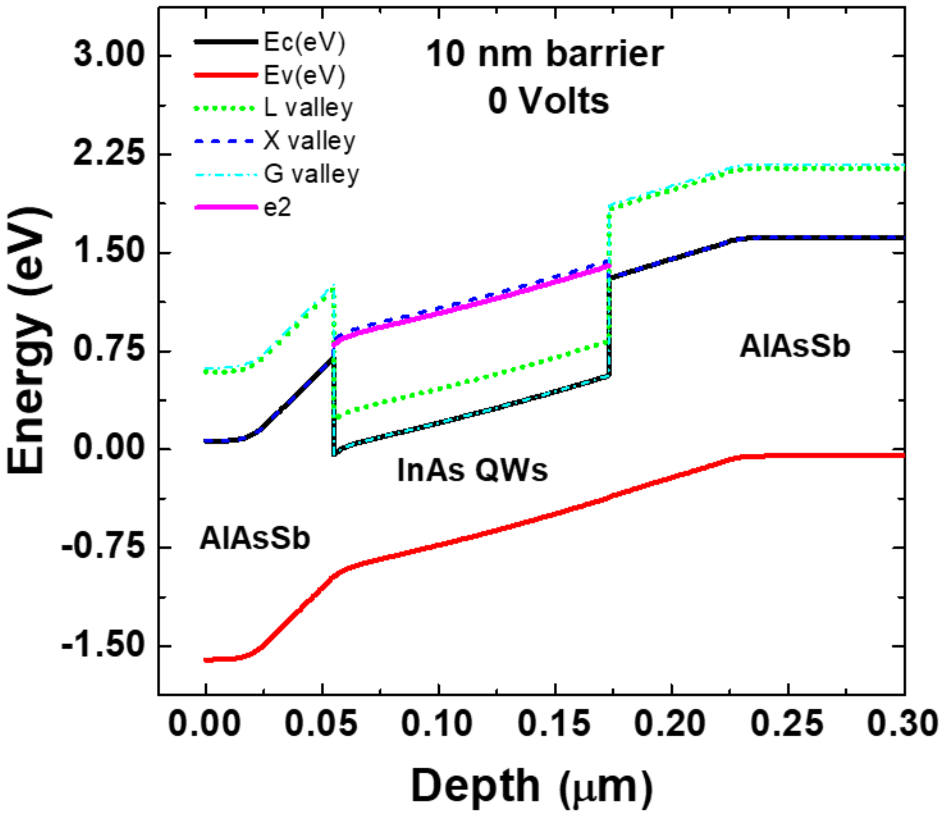
Devices

- InAs Quantum Wells (2.1 nm)
- $AlAs_{0.16}Sb_{0.84}$ Barriers
  - **B080: 2.1 nm**
  - **B081: 5.1 nm**
  - **B082: 10 nm**
- p+ GaAs substrate
- n+ GaSb cap



Devices

- $AlAs_{0.16}Sb_{0.84}$ Barriers
  - ➢ **B080: 2.1 nm**
  - ➢ **B081: 5.1 nm**
  - ➢ **B082: 10 nm**
- Effects of intervalley (IV) scattering vs thermionic emission



J. Tang, *et al*, *Applied Physics Letters* **2015**, 106, 061902

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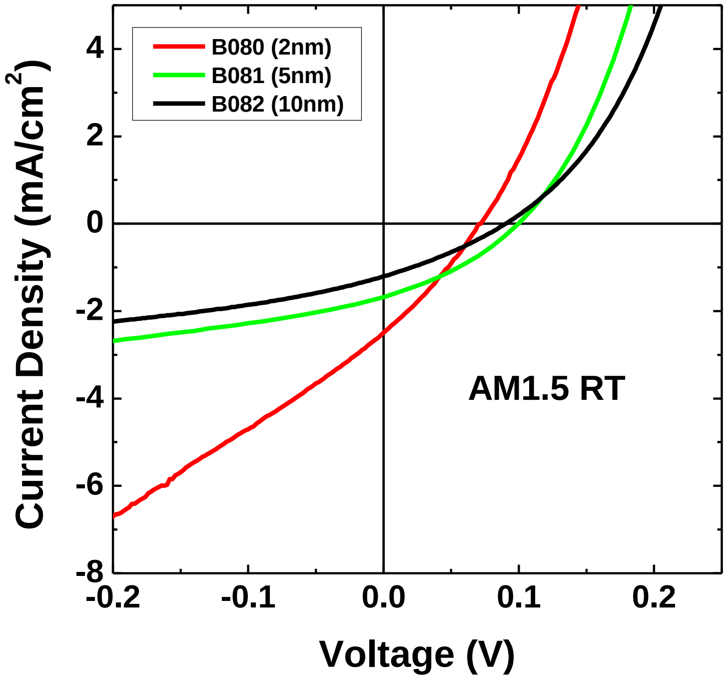
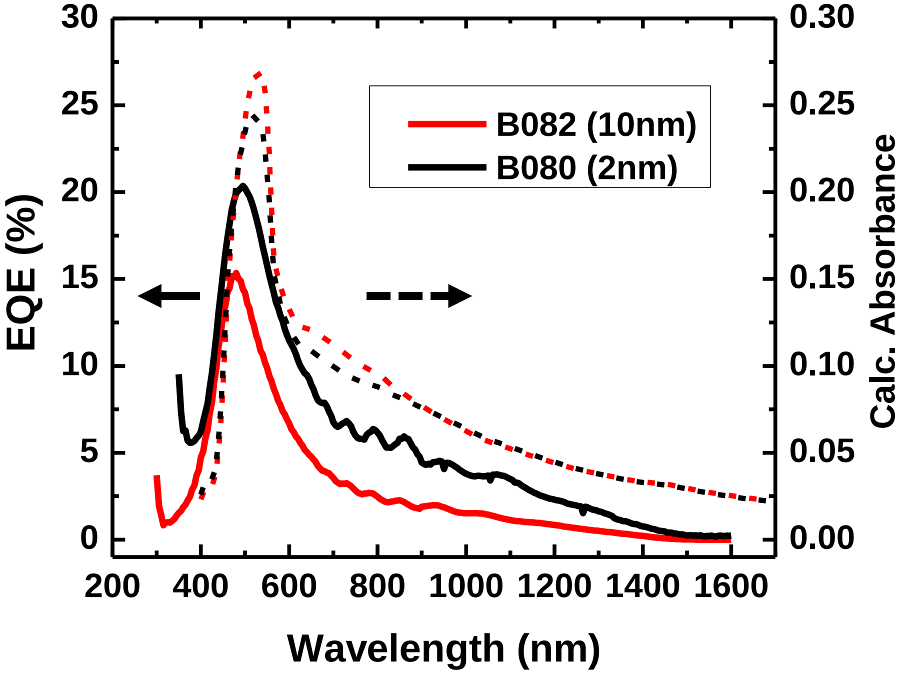
H. Esmaielpour, *et al*, *Scientific Reports* **2018**, 8, 12473

V. R. Whiteside, *et al*, *Semiconductor Science and Technology* **2019**, 34, 094001

Device Current Density-Voltage (JV) Characterisation

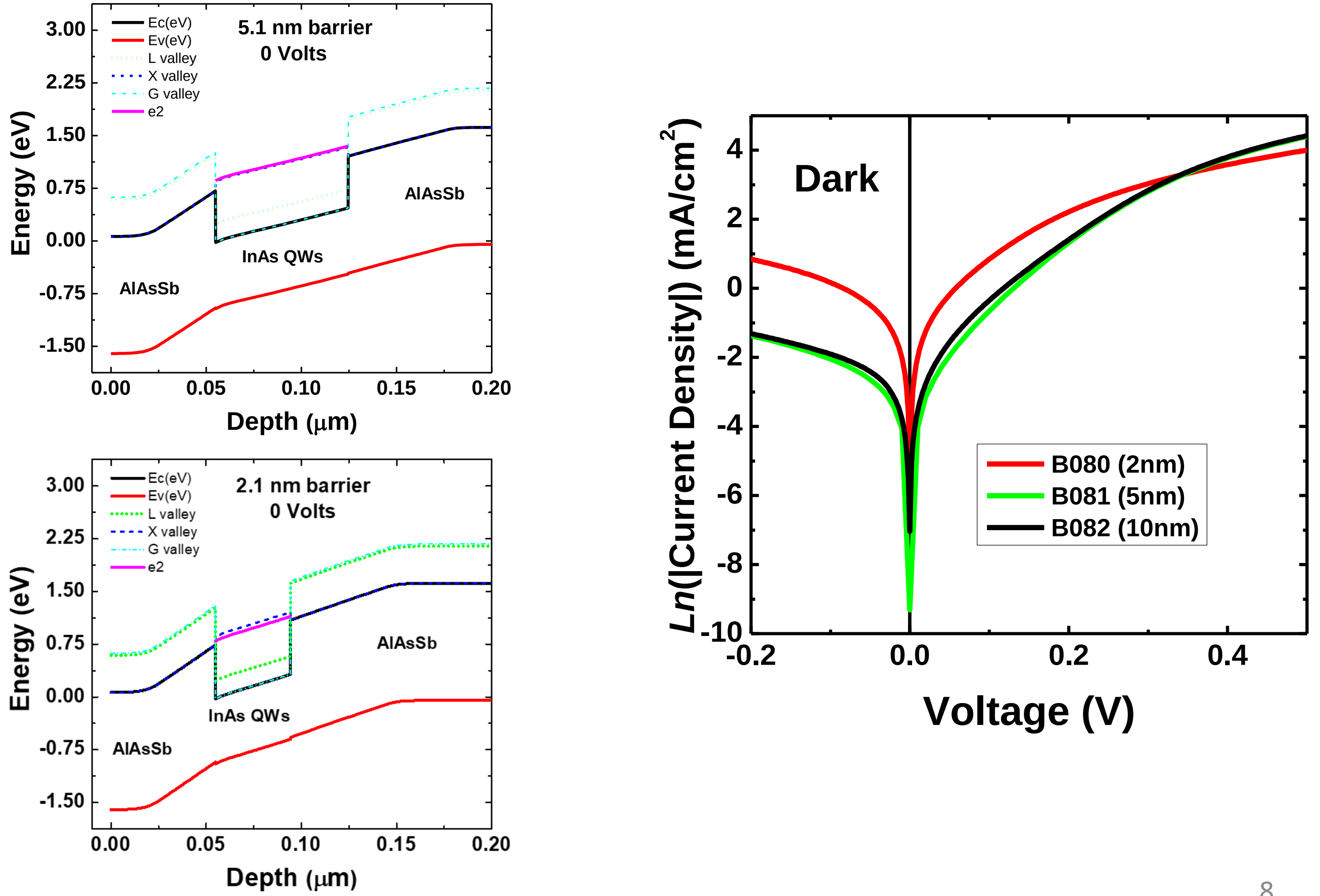
- Extraction of photogenerated carriers increases with decreasing barrier thickness.
- Narrowing depletion region with narrowing barrier





Device Current Density-Voltage (JV) Characterisation

- Extraction of photogenerated carriers increases with decreasing barrier thickness.
- Narrowing depletion region with narrowing barrier
- Equal barrier-quantum well thickness (B080) results in increased tunneling of both photogenerated and majority carriers (lower Voc)

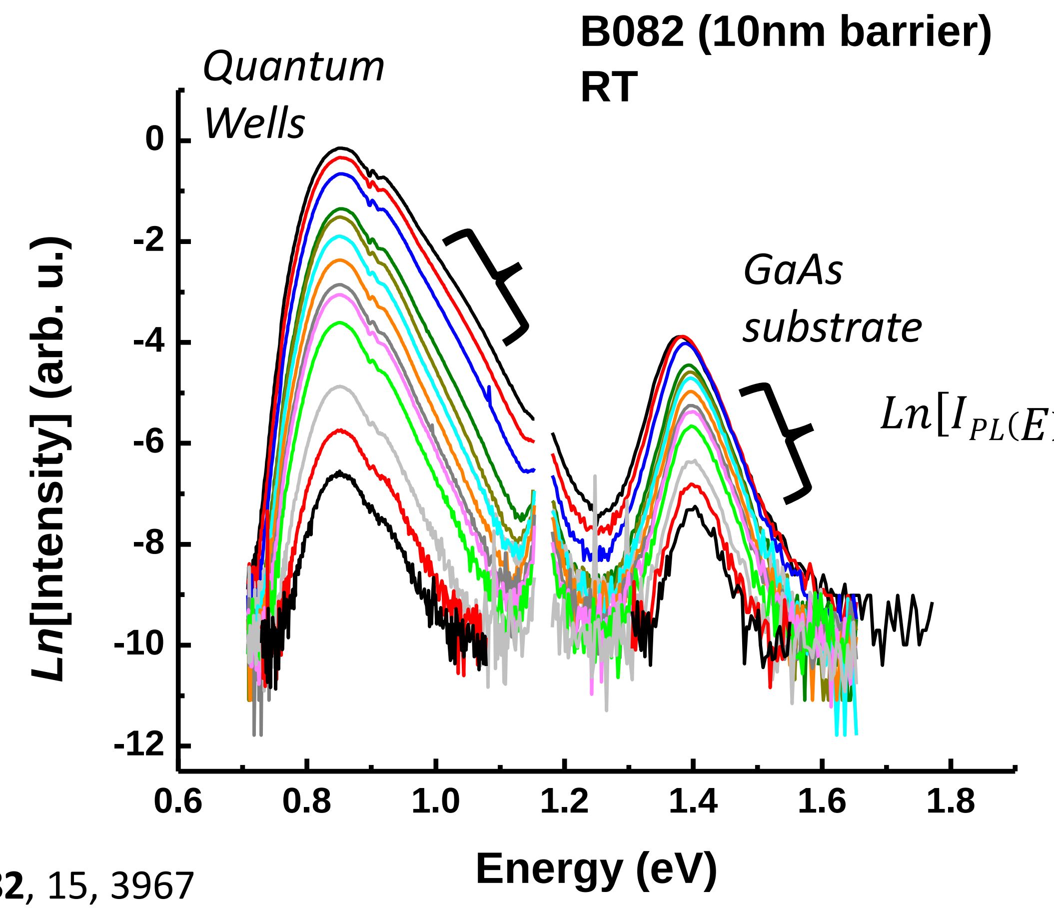


Simultaneous JV/PL

- 532nm Laser (high absorption in device)
- Fitting high energy tail to generalized Planck's law
- Allows for GaAs substrate to be compared

$$I_{PL}(E) = \frac{A(E)E^2}{4\pi^2 h^3 c^2}\left[exp\left(\frac{E-\Delta\mu}{k_B T}\right)-1\right]^{-1}$$

$$Ln[I_{PL(E)}] \propto -\frac{E}{k_B T_{eh}}$$

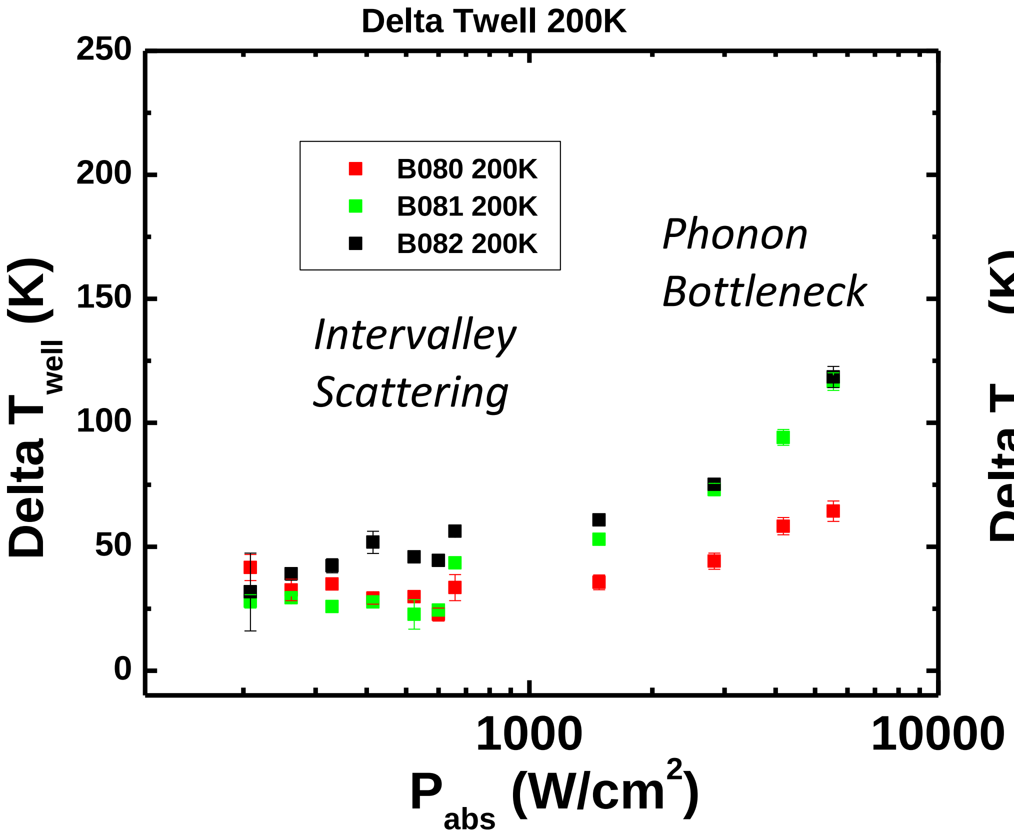


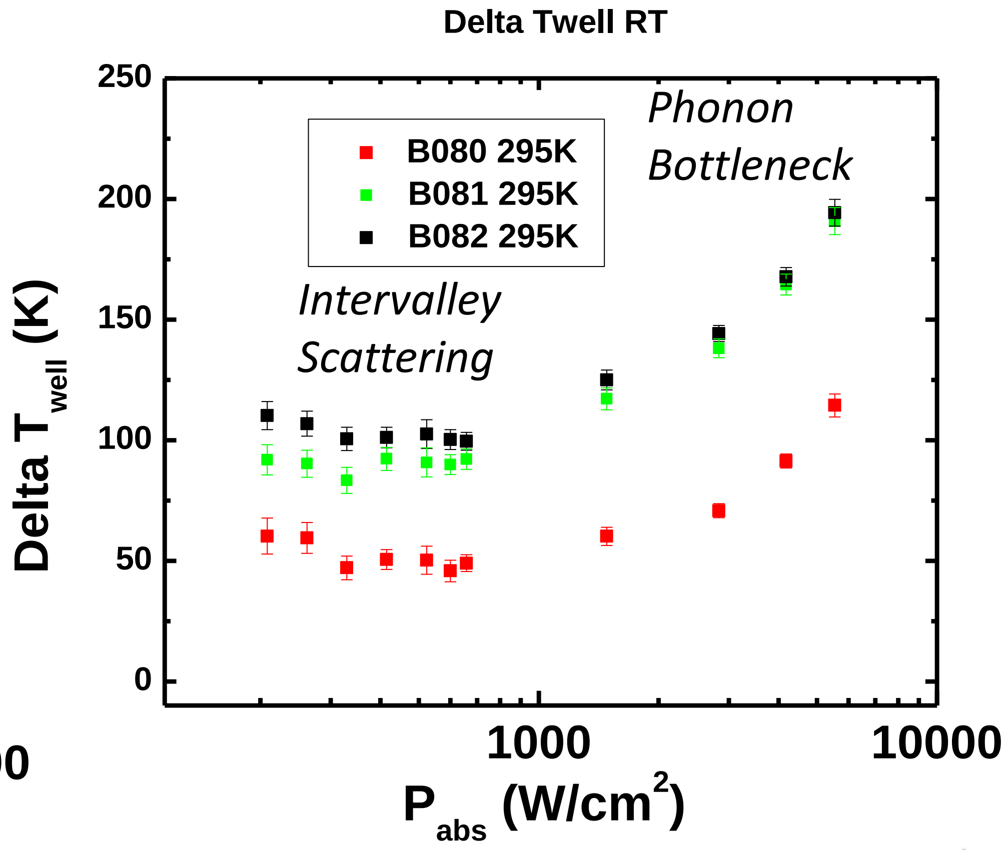
$$Ln[I_{PL(E)}] \propto -\frac{E}{k_B T_L}$$

P. Wurfel, *Journal of Physics C: Solid State Physics* **1982**, 15, 3967
A. Le Bris, *et al, Energy & Environmental Science* **2012**, 5, 6225

Simultaneous JV/PL Carrier Temperatures

- Delta T comparing GaAs slope and Well slope
- Increase in carrier temperature even considering GaAs increase (lattice heating)
- Non-thermalized population at lower carrier generation

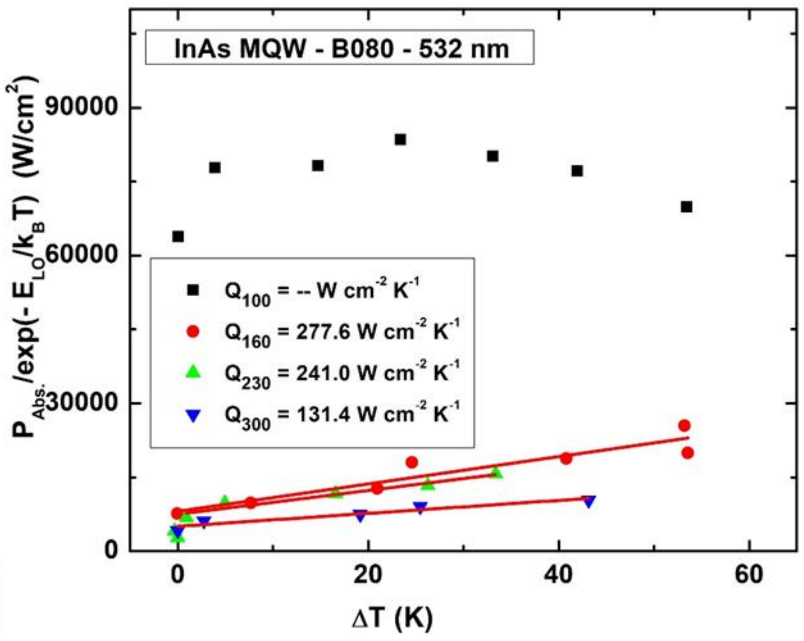




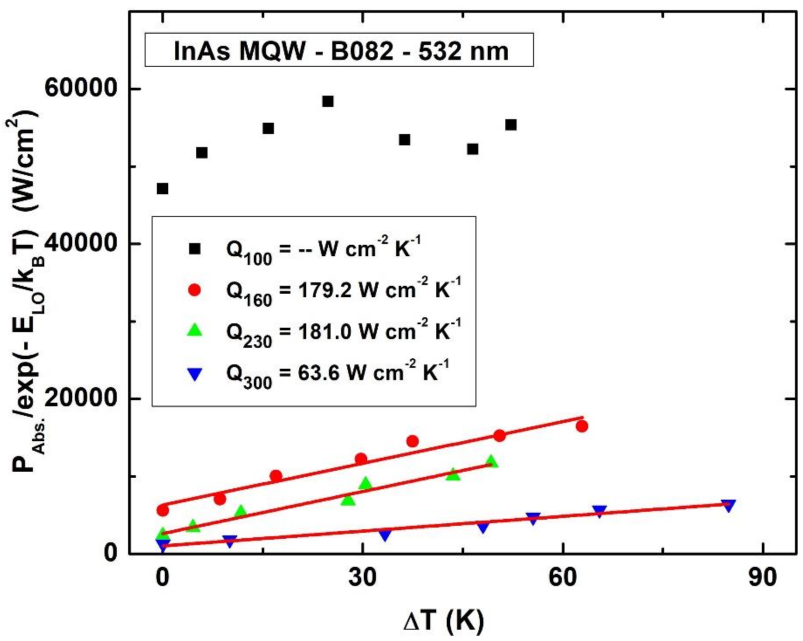
High Resolution PL

- Thermalization coefficient decreases with increasing temperature

2 nm barrier



10 nm barrier



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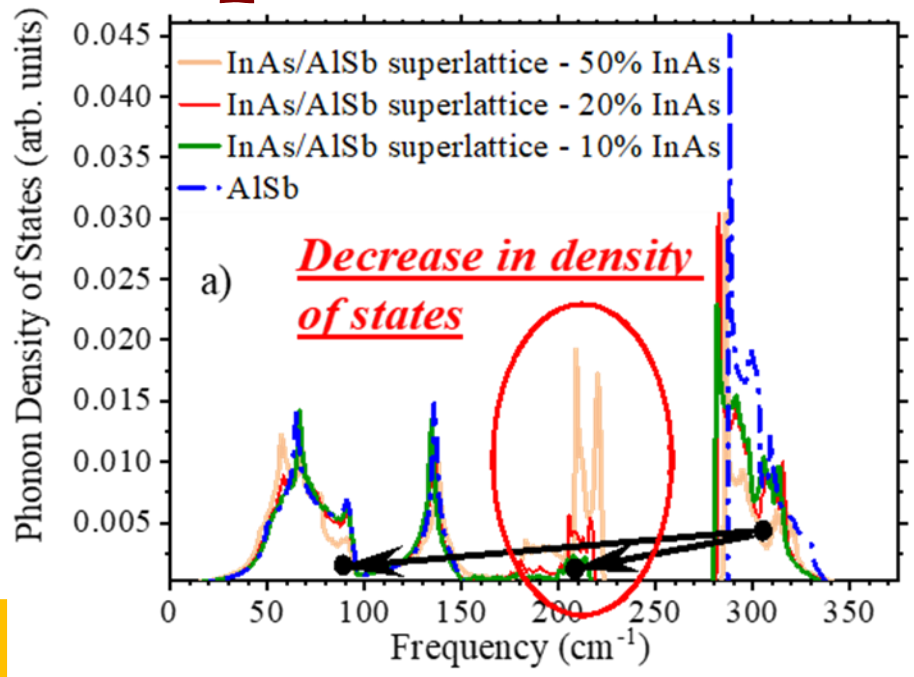
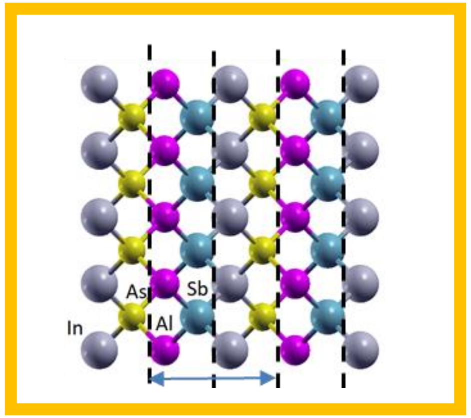
H. Esmaielpour, *et al*, *Progress in Photovoltaics: Research and Applications* **2016,** 24, 591

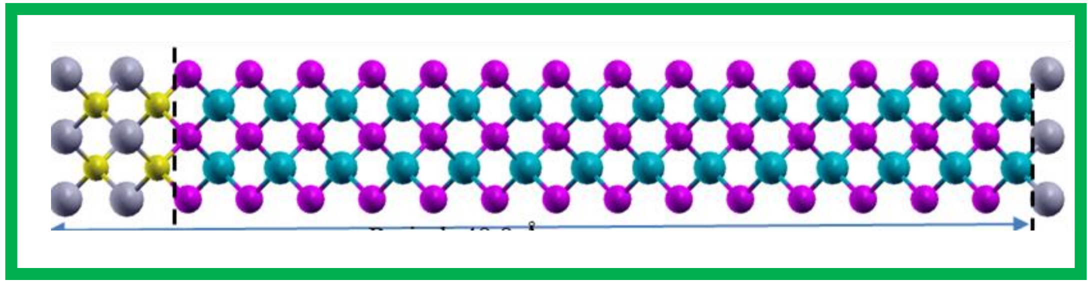
Simultaneous JV/PL Carrier Temperatures

- Thermalization Coefficient decreases with increasing temperature
- Increasing barrier thickness lowers phonon density of states
- Supports "bottleneck" in phonon mediated thermalization



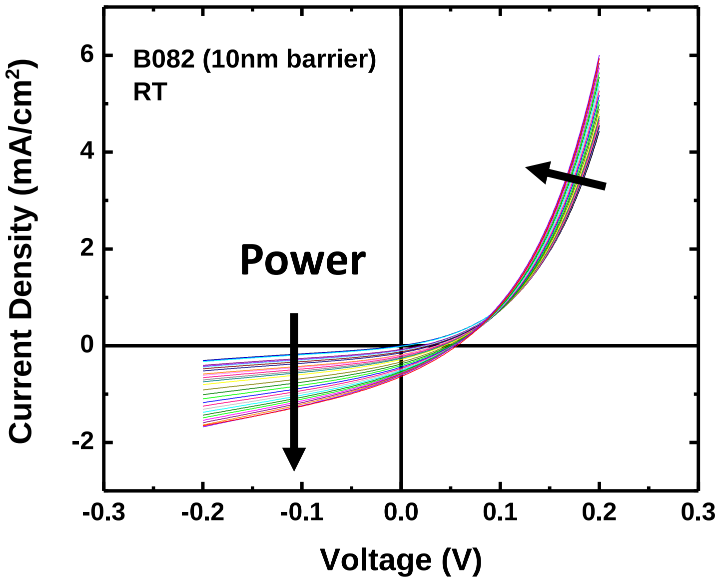
J. Garg, I. R. Sellers, *Semiconductor Science and Technology* **2020,** 35, 044001

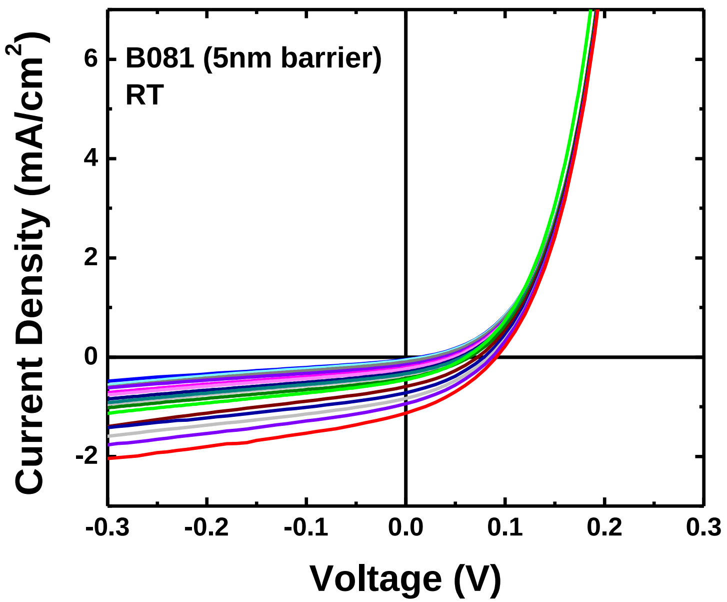


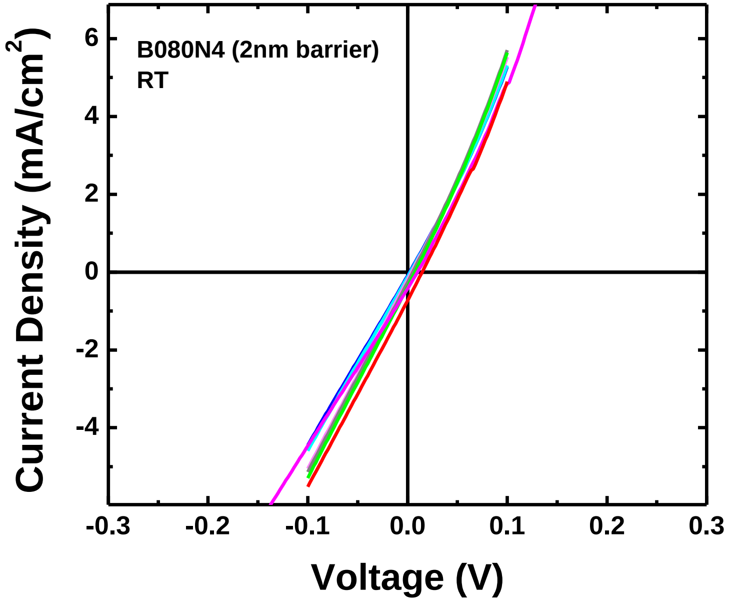


Simultaneous JV/PL

- Increased photocurrent as well as forward bias current
- B080 (2nm) leakage current hinders performance

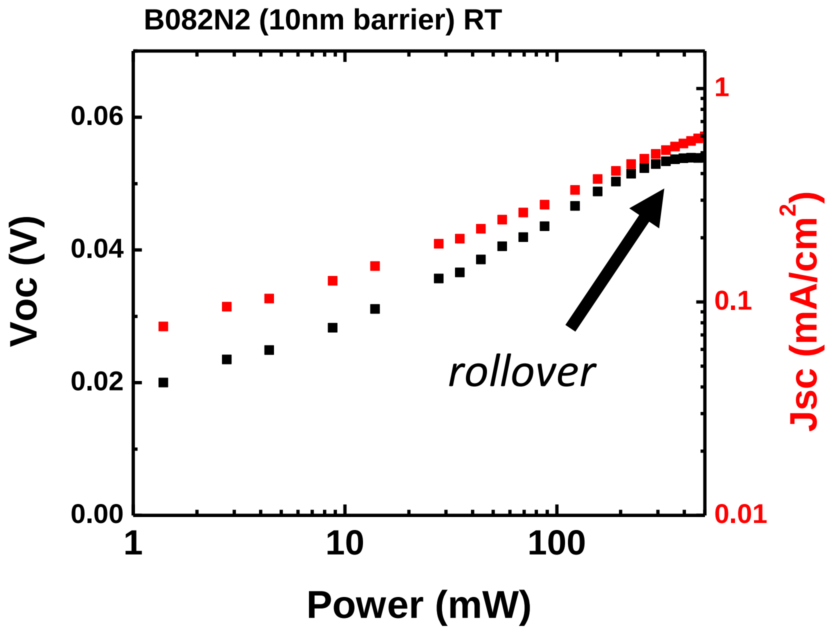


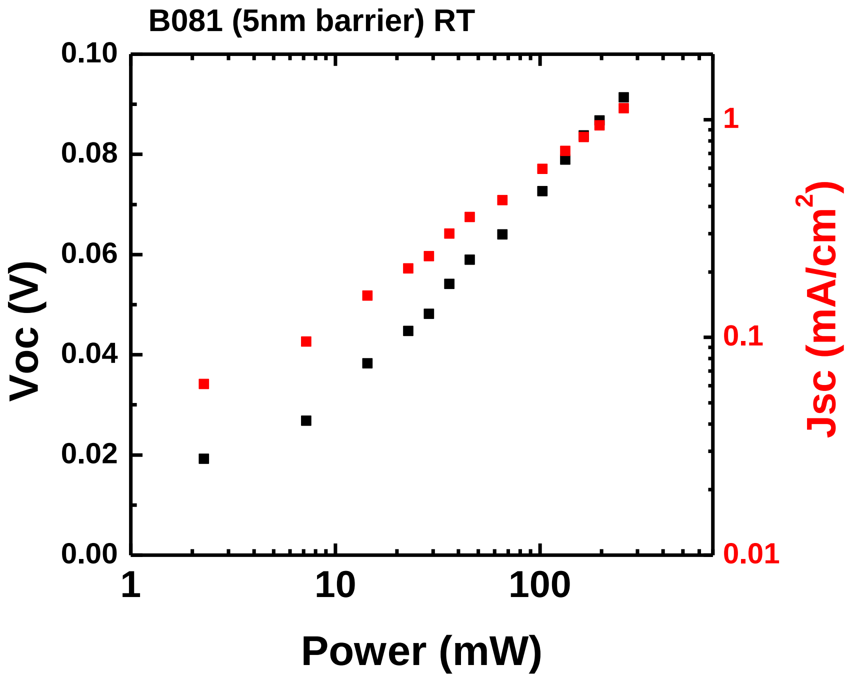


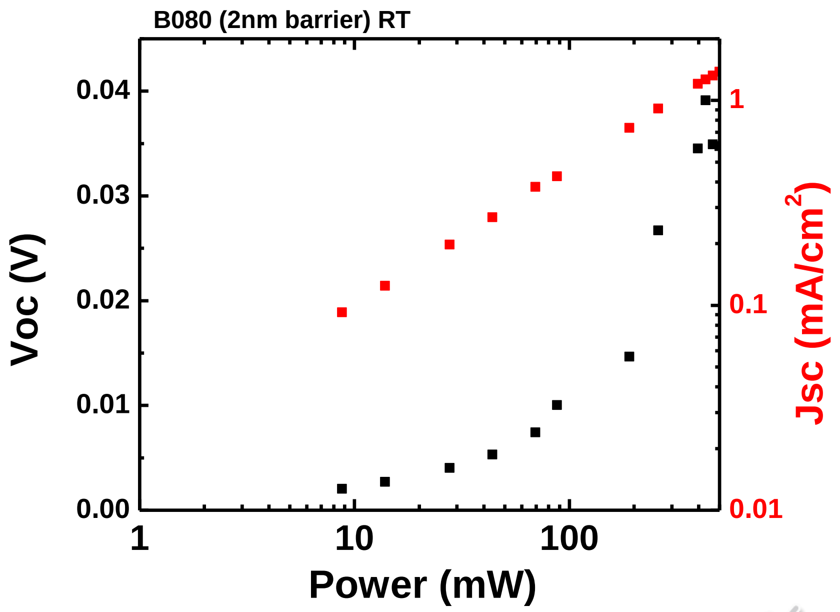


Simultaneous JV/PL

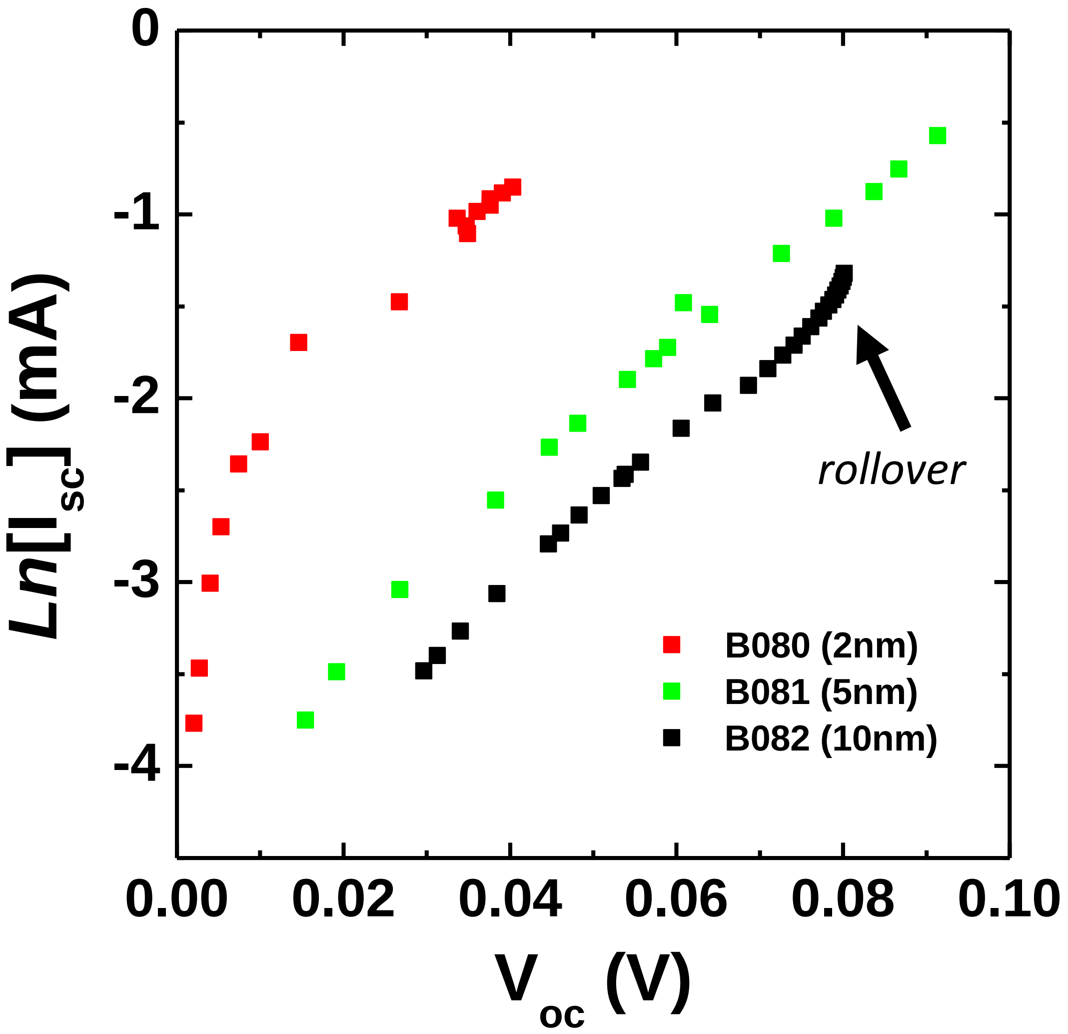
- Jsc increase greatest for thinnest barrier, less for deep confined QW (B082)
- Voc "rollover" noticeable at high powers







Simultaneous JV/PL



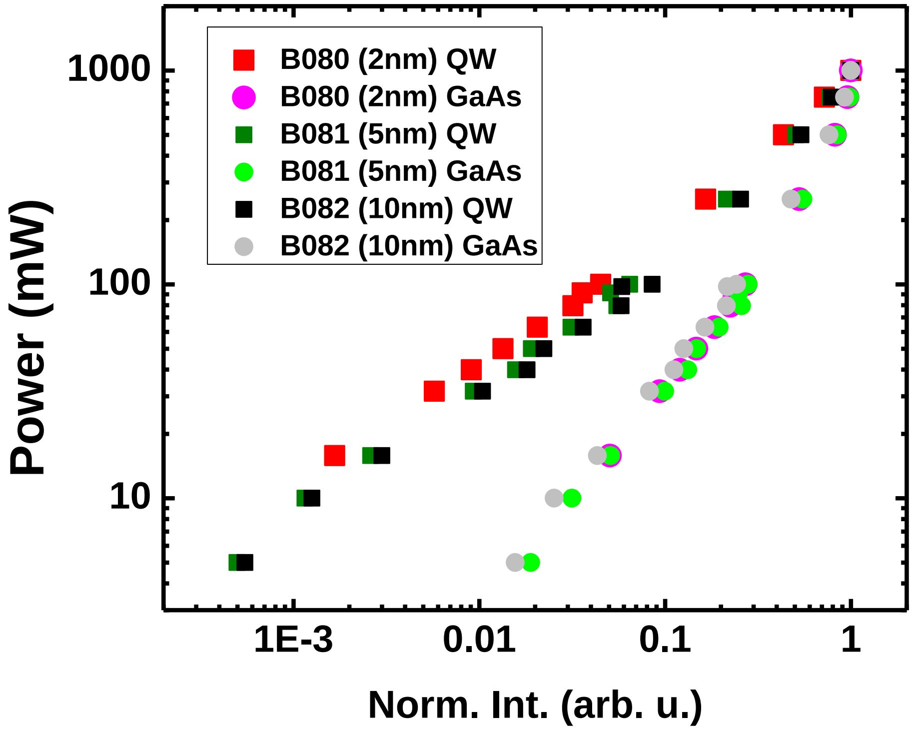
Ideality factors:

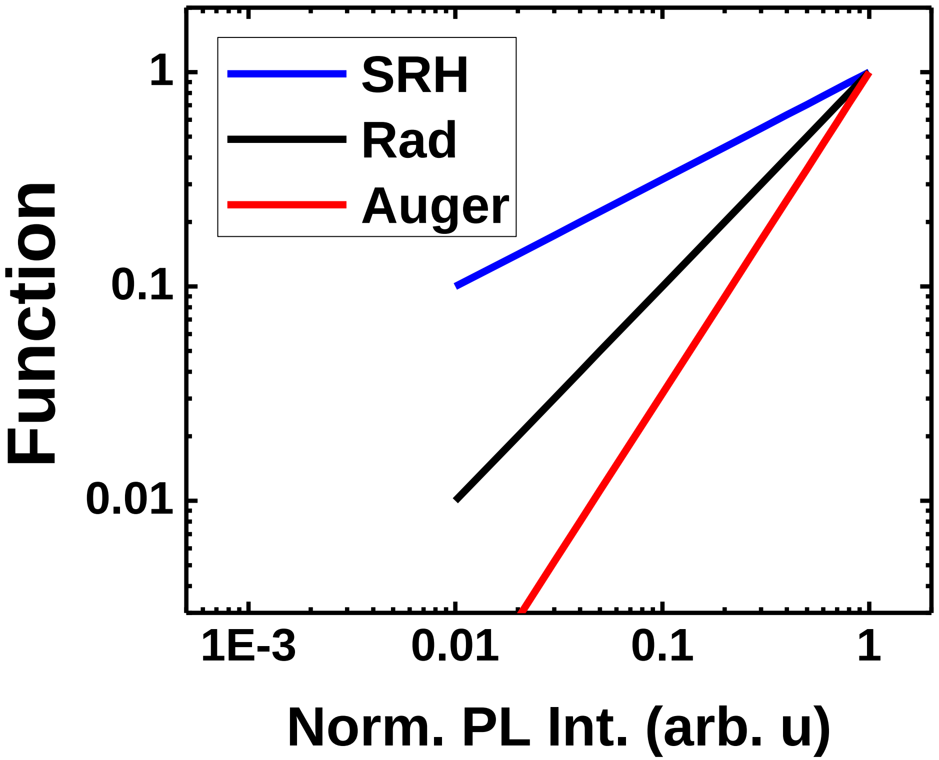
- B080 (2nm): 1.19
- B081 (5nm): 1.07
- B082 (10nm): 1.17

Simultaneous JV/PL

$$P_{ex} = P1(I_{PL})^{1/2} + P2(I_{PL}) + P3(I_{PL})^{3/2}$$

P1: SRH, P2: Radiative, P3: Auger





Tang, J.; *et al, Applied Physics Letters* ***2015,*** 106 (6), 061902
Yoo, *et al, Applied Physics Letters* ***2013***, 102 (21), 211107.

Simultaneous JV/PL

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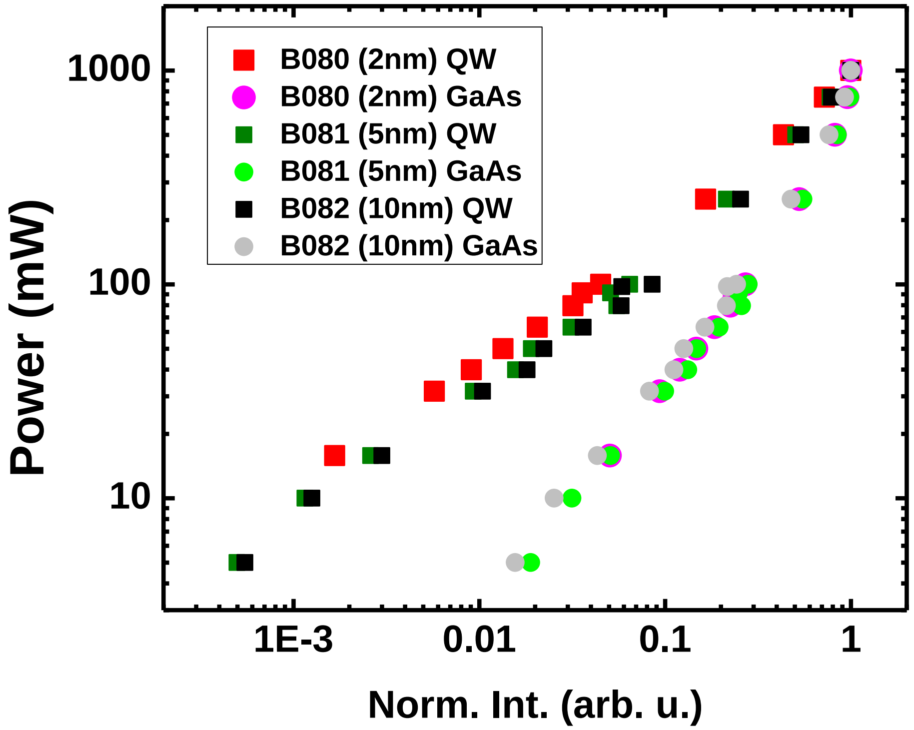

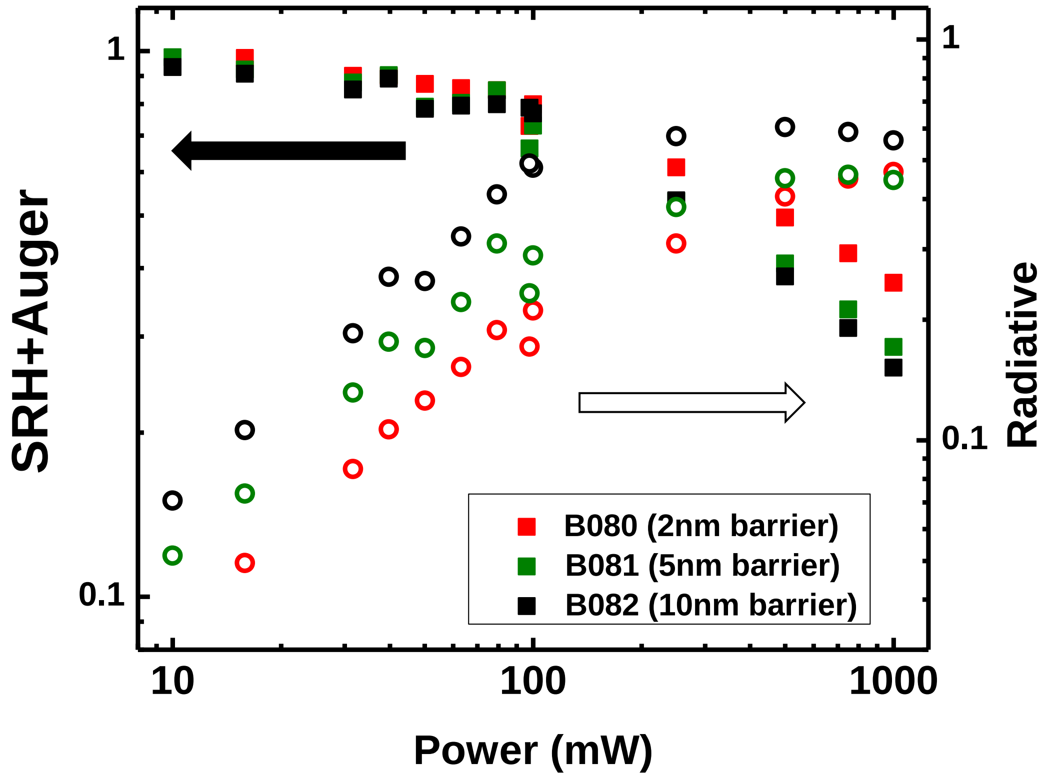

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Yoo, *et al, Applied Physics Letters* ***2013***, 102 (21), 211107.

Conclusions

- InAs Quantum Well carrier temperatures elevated when compared to the GaAs substrate luminescence (T_C vs T_L)
- Intervalley scattering possible explanation for higher extracted well temperature at lower powers
- Phonon bottleneck probable at higher temperatures and powers
- JV characterization shows decreased extraction with barrier thickness
- High powers near radiative limit but Voc plateaus

Acknowledgements

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