The Role of Valley Degeneracy in Carrier Extraction in Valley Photovoltaic Solar Cells

Kyle R. Dorman, ***Vincent R. Whiteside, David K. Ferry, Israa G. Yusuf, Tanner J. Legvold, Tetsuya D. Mishima, Michael B. Santos, Stephen J. Polly, Seth M. Hubbard, and Ian R. Sellers***

Homer L. Dodge Department of Physics & Astronomy, University of Oklahoma, Norman, Oklahoma 73019, USA
School of Electrical, Computer, and Energy Engineering, Arizona State University, Tempe, Arizona 85287-5706, USA
NanoPower Research Labs (NPRL), Rochester Institute of Technology, Rochester, NY 14623, USA

@SellersPVGroup

- Hot Carriers and Band Structure
- Intervalley Scattering and the Gunn Effect
- Potential Device Structures
- Band Alignments and Barriers
- Future Work

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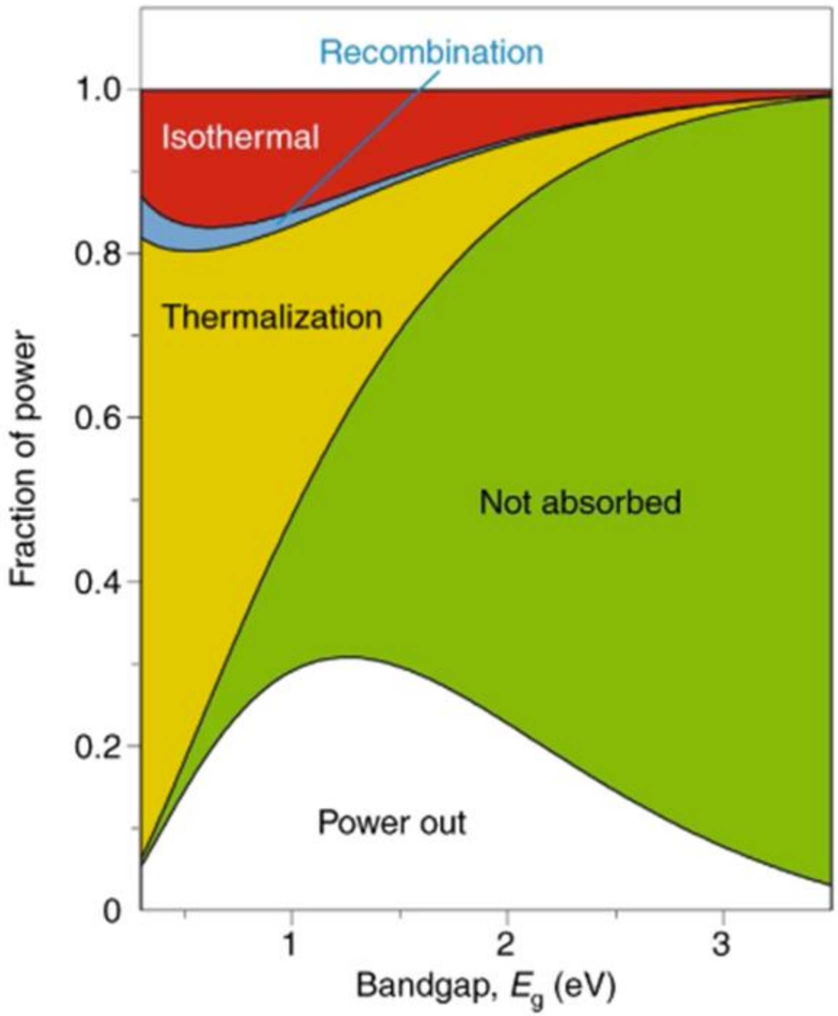
Photovoltaics Materials & Device Group, University of Oklahoma: http://www.nhn.ou.edu/~sellers/group/index.html

Introduction

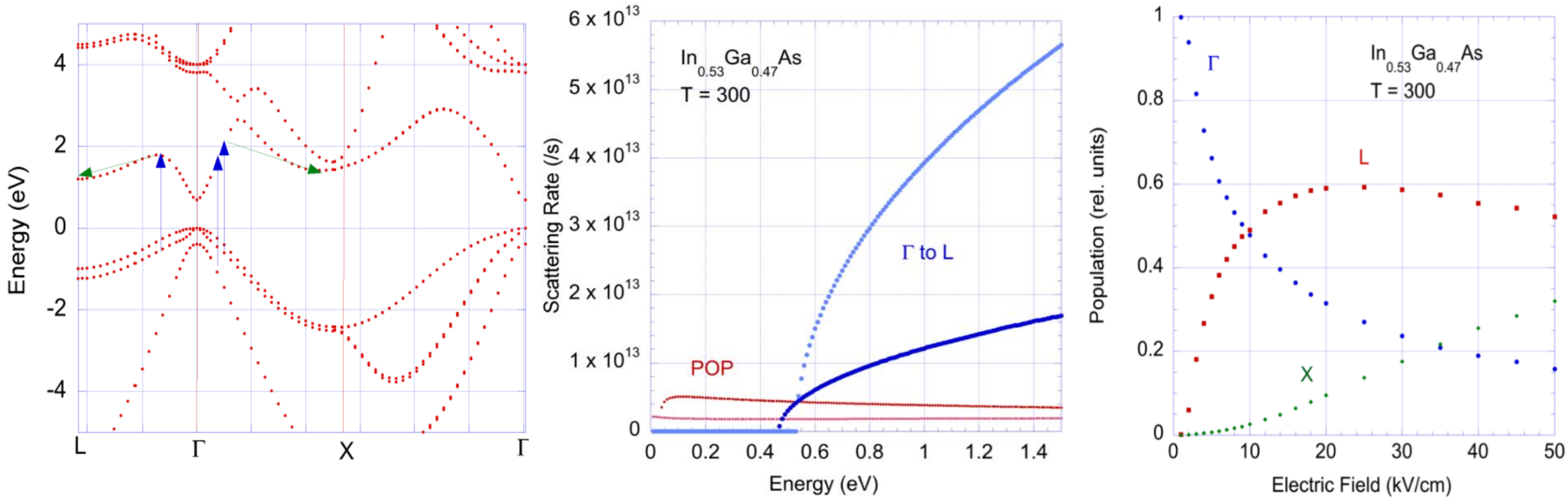


Guillemoles, J., Kirchartz, T., Cahen, D. *et al.* Guide for the perplexed to the Shockley–Queisser model for solar cells. *Nat. Photonics* **13,** 501–505 (2019). https://doi.org/10.1038/s41566-019-0479-2

- Single gap solar cells are limited to ~30% efficiency
- Photons above the bandgap will generate “hot carriers” that swiftly thermalize
- A hot carrier solar cell addresses *thermalization loss* by extracting those high energy electrons

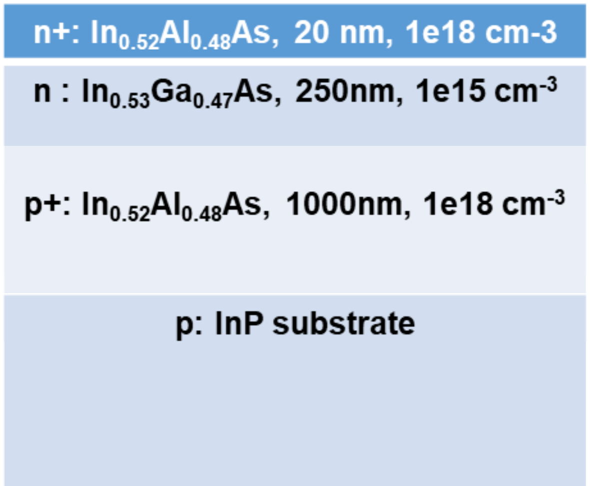
Valley Photovoltaics: Intervalley Scattering

David K. Ferry, ASU. “In Search of a True Hot Carrier Solar Cell,”
D K Ferry, Semicond. Sci. Technol. Vol. **34** no. 4 (2019).

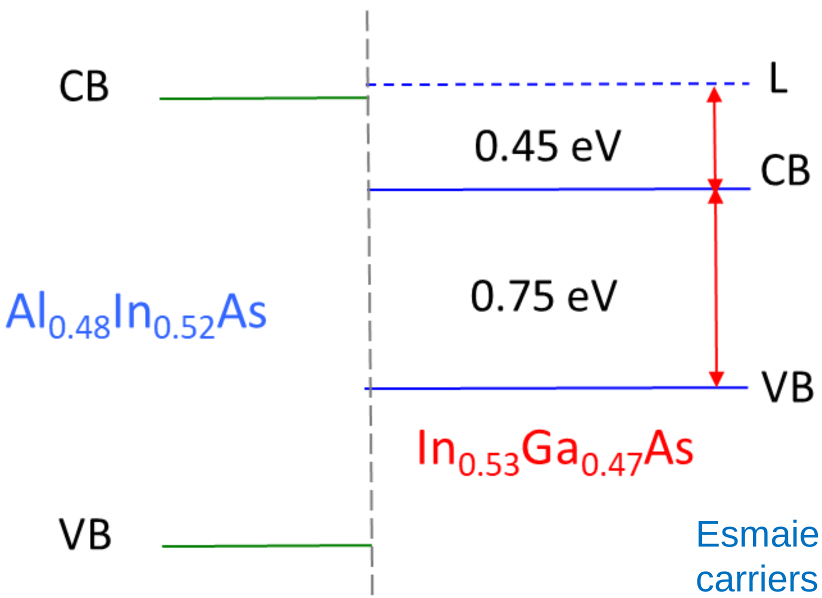


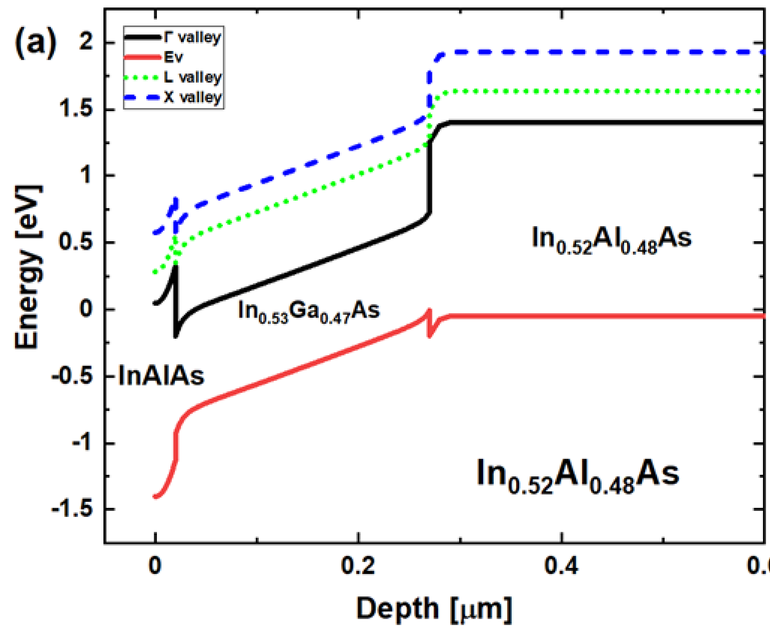
- High energy electrons: Intervalley scattering
- Low energy electrons: The Gunn Effect
- Transfer, store, and extract via upper valleys!

Device Structure



- Need a resonant barrier material with InGaAs, and an absorber with both a bandgap and an L valley in the solar spectrum.

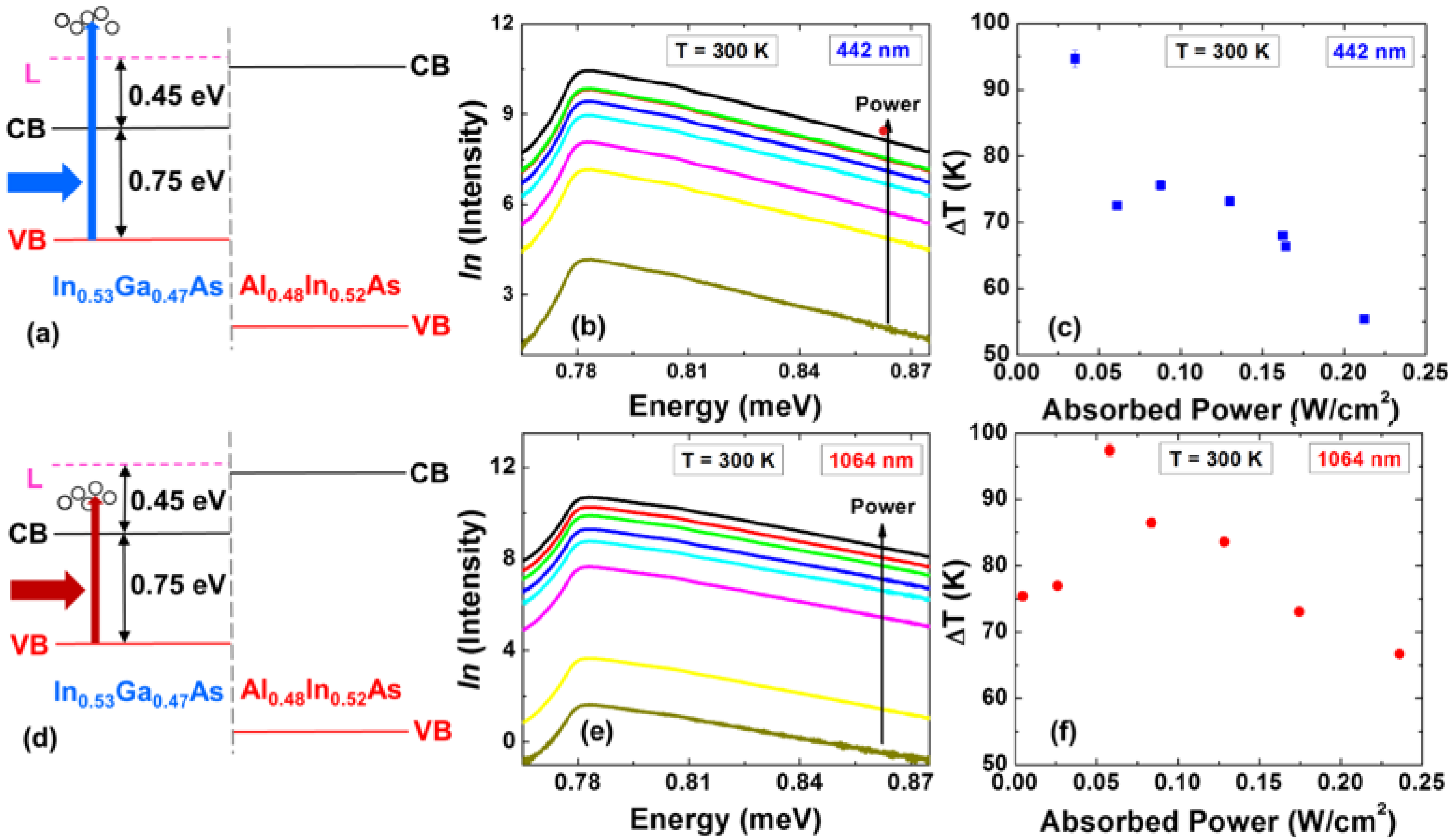




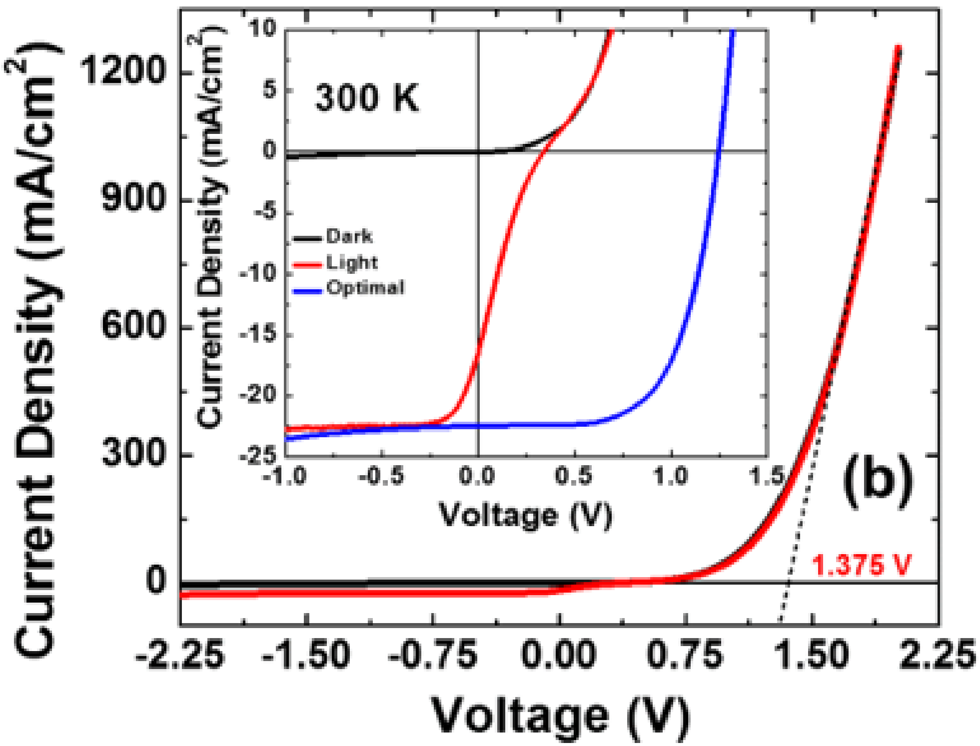
Esmaielpour et al., "Exploiting intervalley scattering to harness hot carriers in III–V solar cells," Nature Energy **5,** 336-343 (2020).

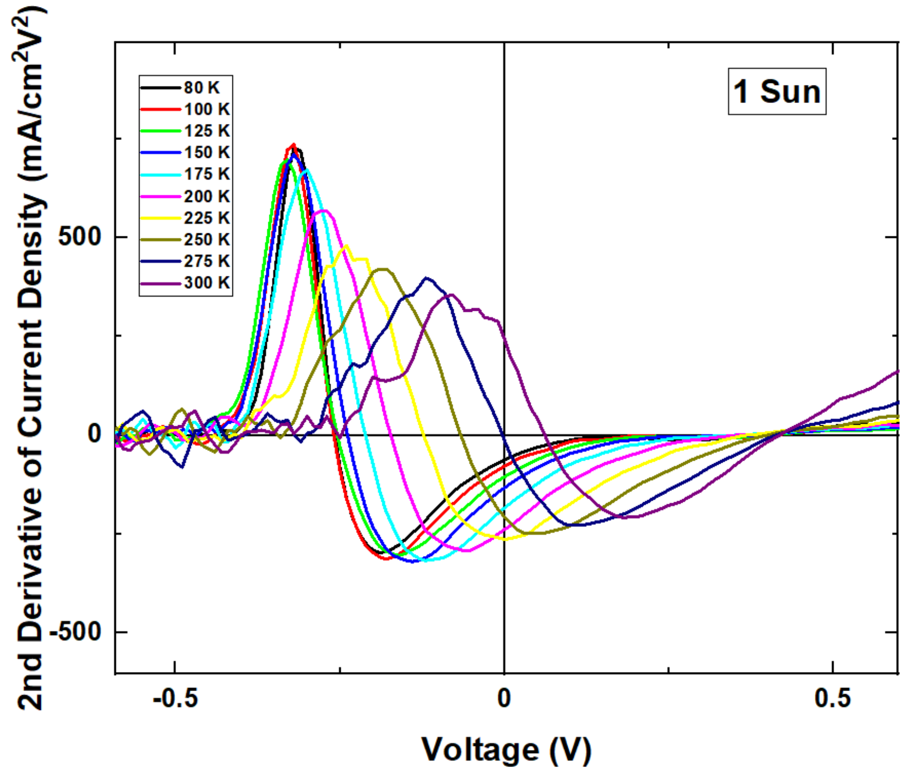
Evidence of Hot Carriers

- The carrier temperature in the device can be quantified by fitting the high energy tail of the photoluminescence spectrum to the generalized Planck relation: $I(E) = \varepsilon(E) \cdot \exp\left[\frac{-E}{k_B T_c}\right]$



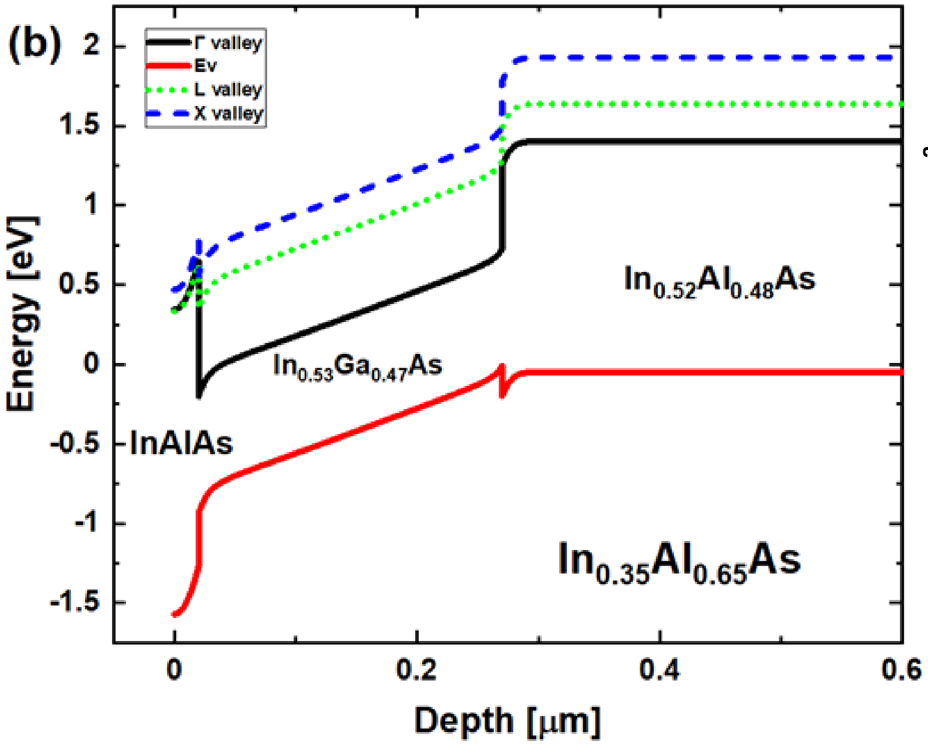
Role of Valley Degeneracy at Absorber/Barrier Interface

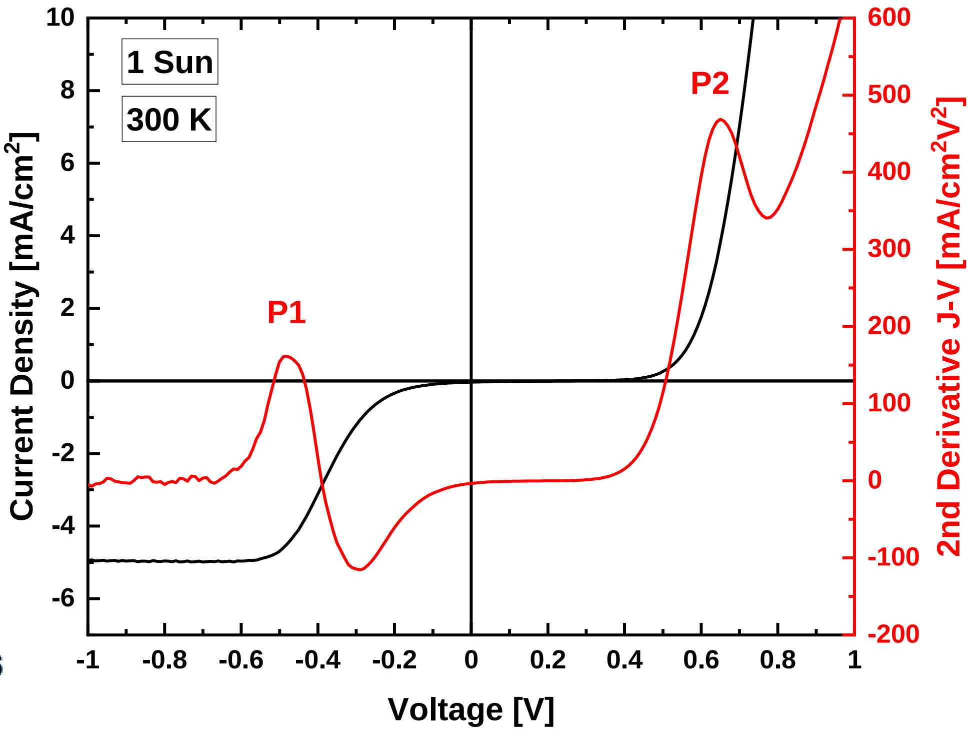




- Initial suggestion: L of the absorber to Γ of the top layer is not an efficient transition.

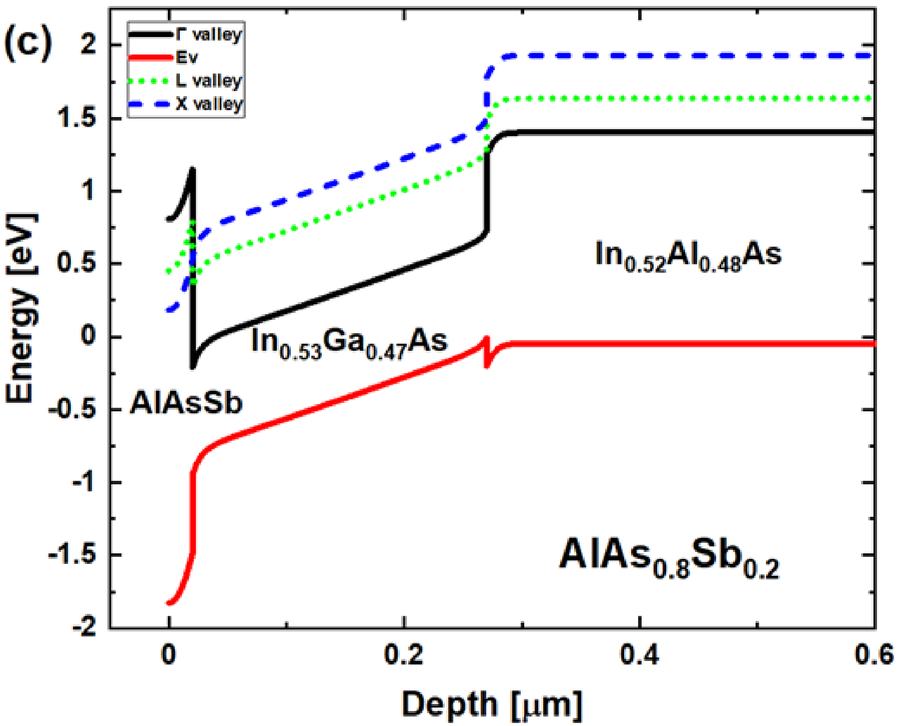
Design Alterations

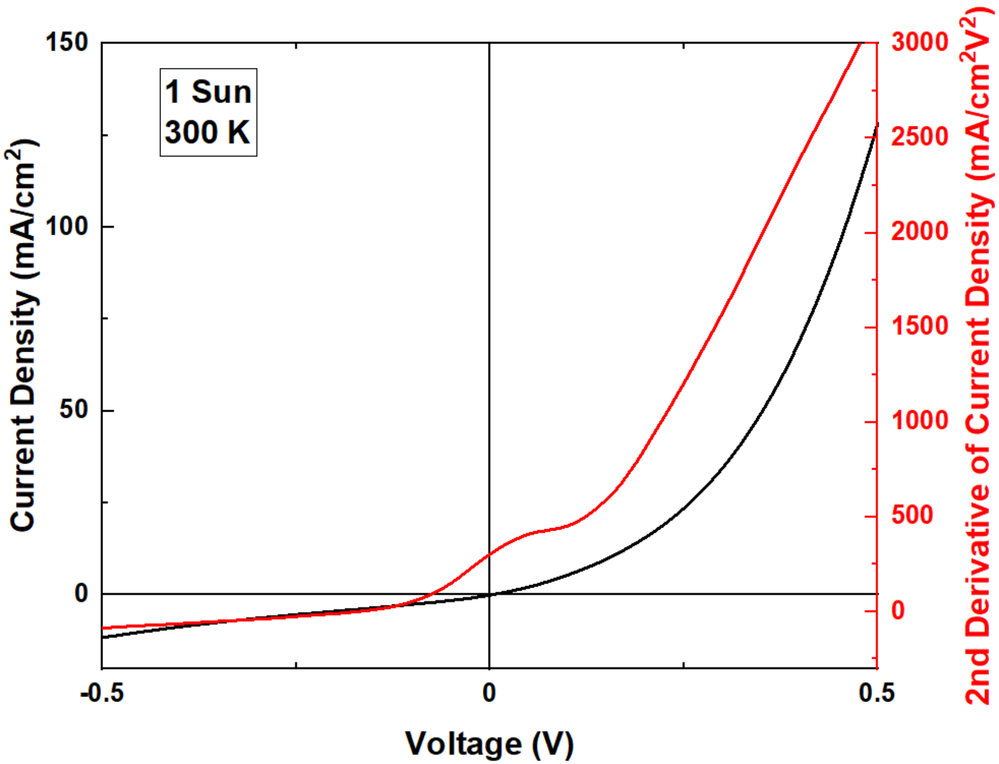




- The L valley is slightly below the Γ valley.
- 2[nd] Derivative analysis indicates two barriers.

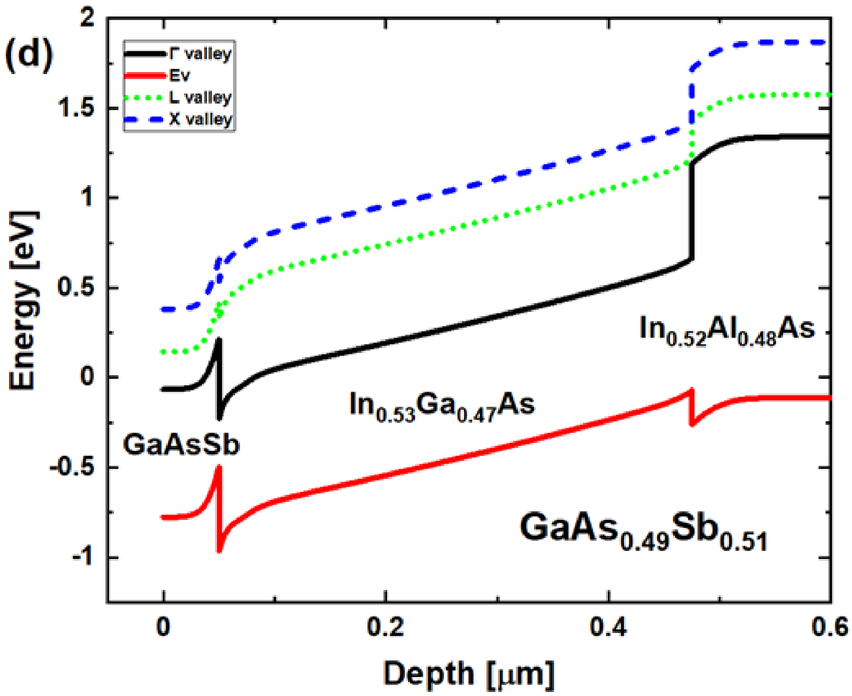
X to X Alignment

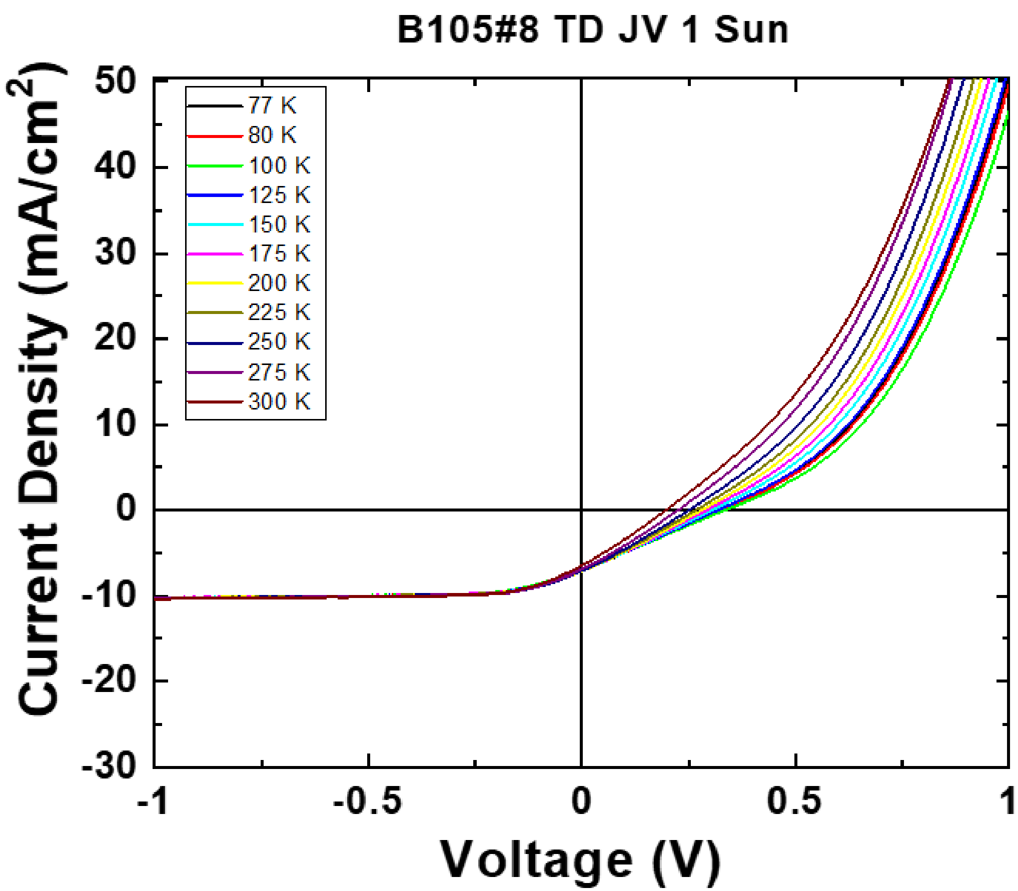




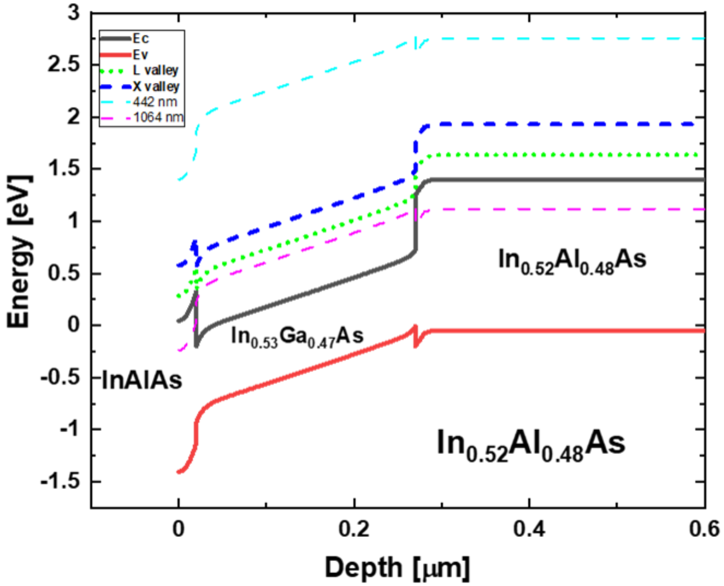
- Amazing line up here!
- Minority carrier extraction is quenched.

L to L Alignment

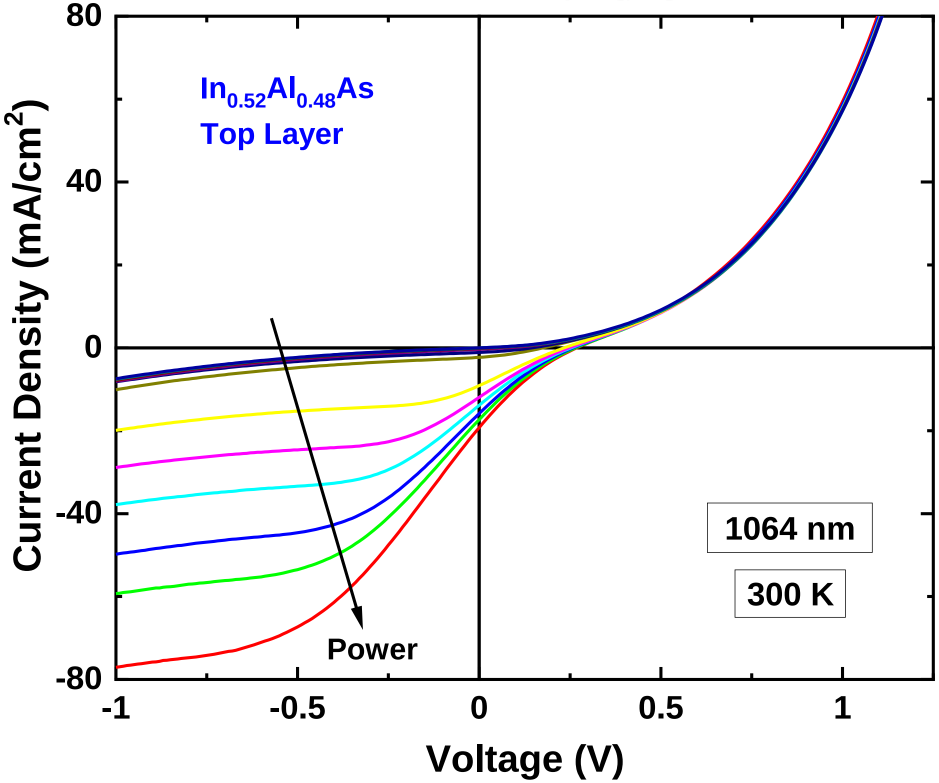


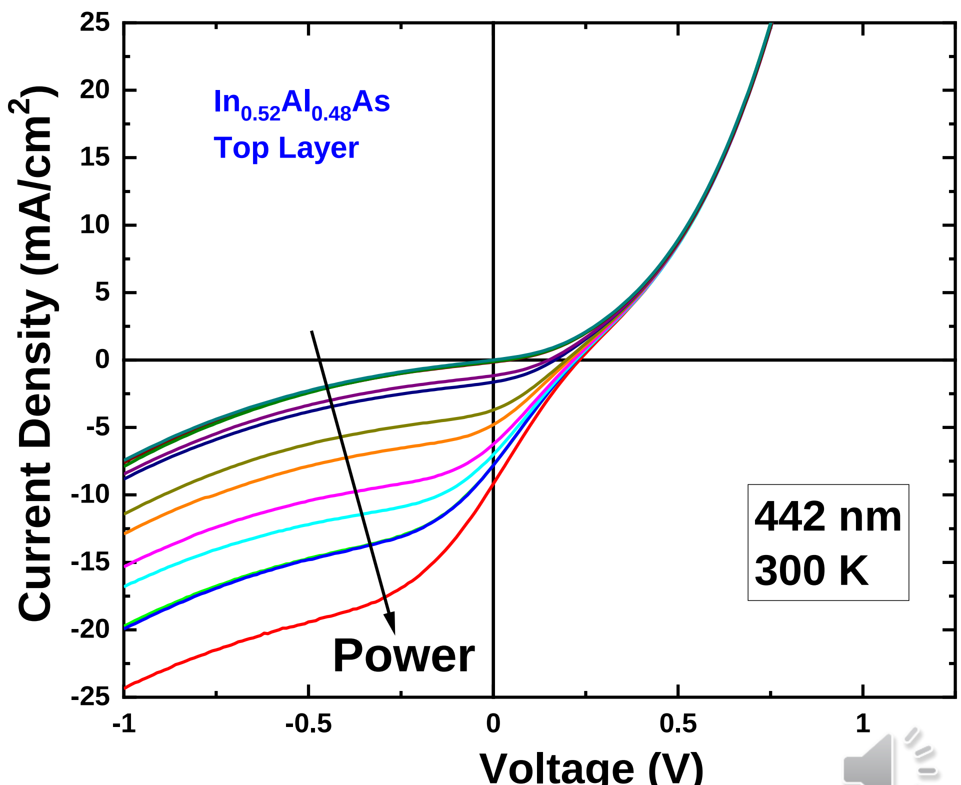


- The L valley of InGaAs is more accessible than the X.

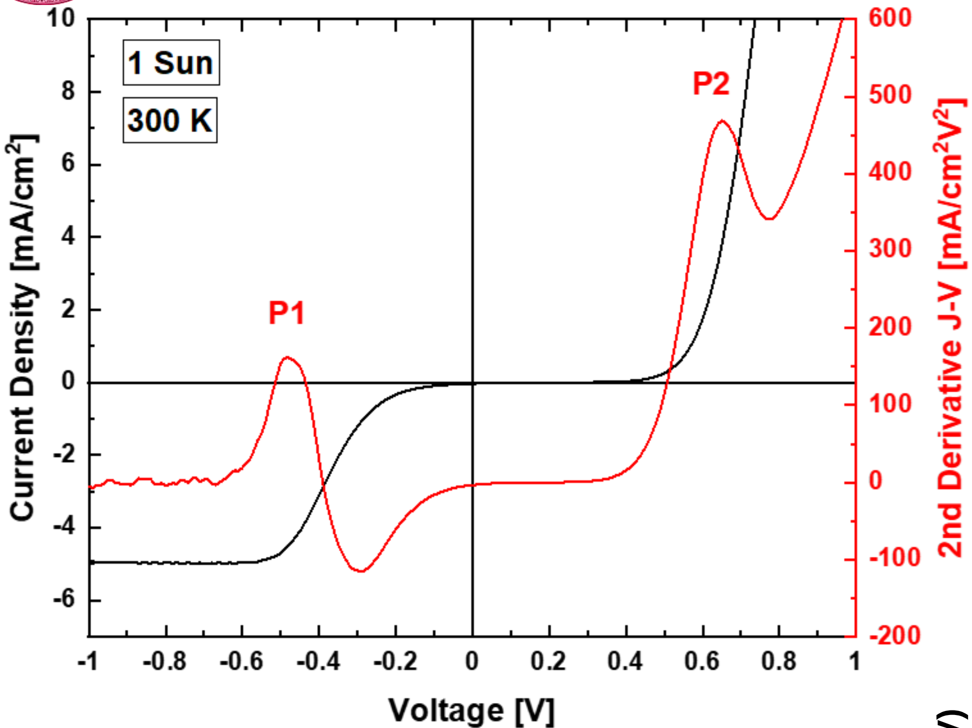


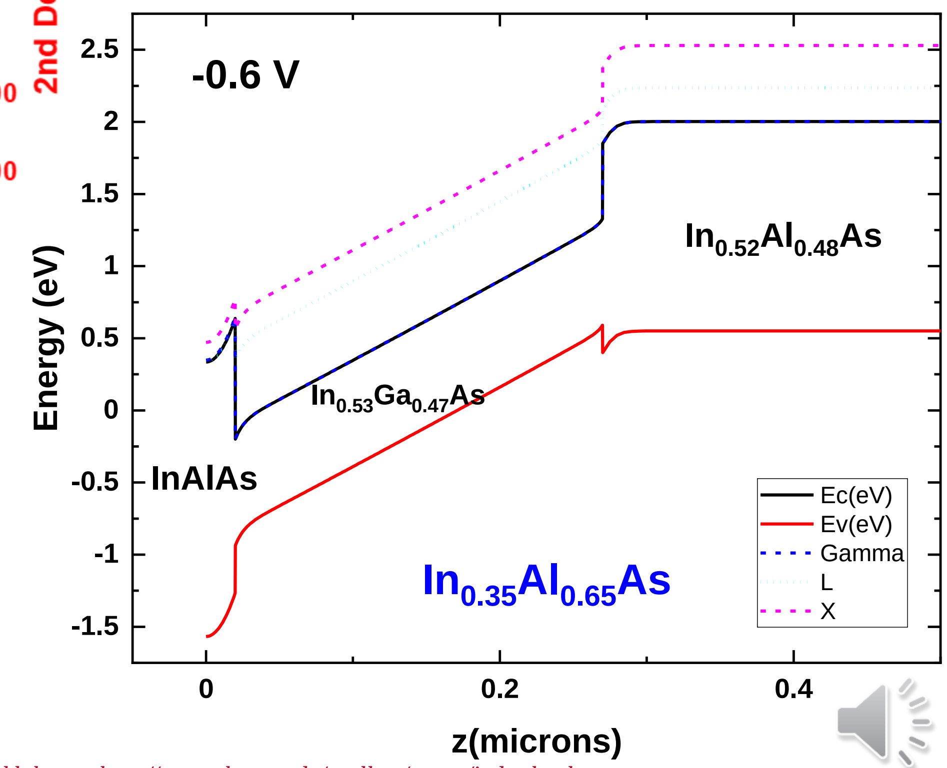
- We can excite above and below the valleys…
- And we don't obtain substantially different results!





Upper Valley Extraction





- The efficient pathway is still the Γ valley.
- We need a way to efficiently pass current from the upper valley.

Conclusions and Acknowledgments

- Valley photovoltaics has demonstrated maintenance of hot carrier populations under practical conditions for solar cell operation.
- InGaAs serves well as an absorber material, but modifications to the top layer and the extraction pathway are necessary to advance the design.
- Extraction of hot carriers through the upper valleys of the top layer appears to require more than band alignment alone.
- Further understanding of the operation of those transitions or development of energy selective contacts may be required.

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