Electric Field and its Effect on Hot Carriers in InGaAs Valley Photovoltaic Devices

***Kyle R. Dorman**, Vincent R. Whiteside, David K. Ferry, Tetsuya D. Mishima, Israa Yusuf, Hamidreza Esmaielpour, Michael B. Santos, Ian R. Sellers*

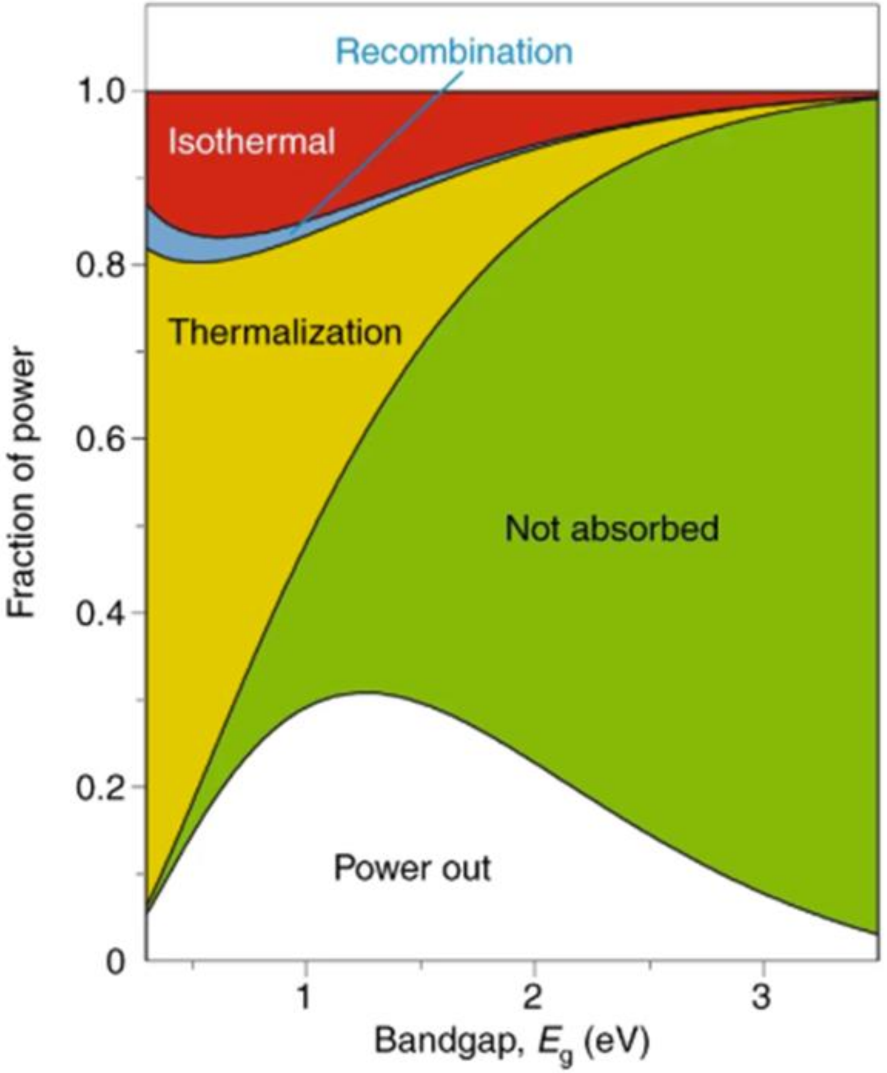
Homer L. Dodge Department of Physics & Astronomy, University of Oklahoma, Norman, Oklahoma 73019, USA
School of Electrical, Computer, and Energy Engineering, Arizona State University, Tempe, Arizona 85287-5706, USA
Walter Schottky Institut, Technische Universität München, Am Coulombwall 4, D-85748 Garching, Germany

- Hot Carriers and Band Structure
- Intervalley Scattering and the Gunn Effect
- Electric Field Effects
- Electrical and Optical Measurements
- Hot Carrier Behavior
- Future Work

@SellersPVGroup

49th IEEE Photovoltaic Specialists Conference, Philadelphia, PA • June 5-10, 2022

Introduction

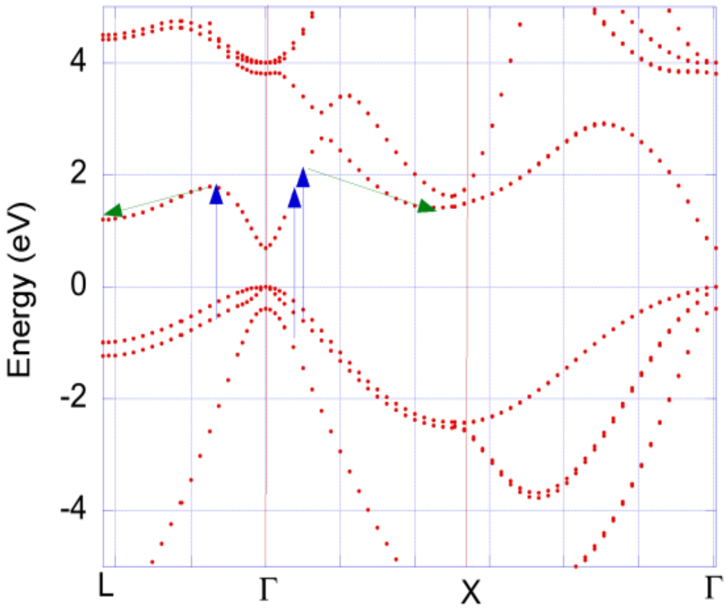


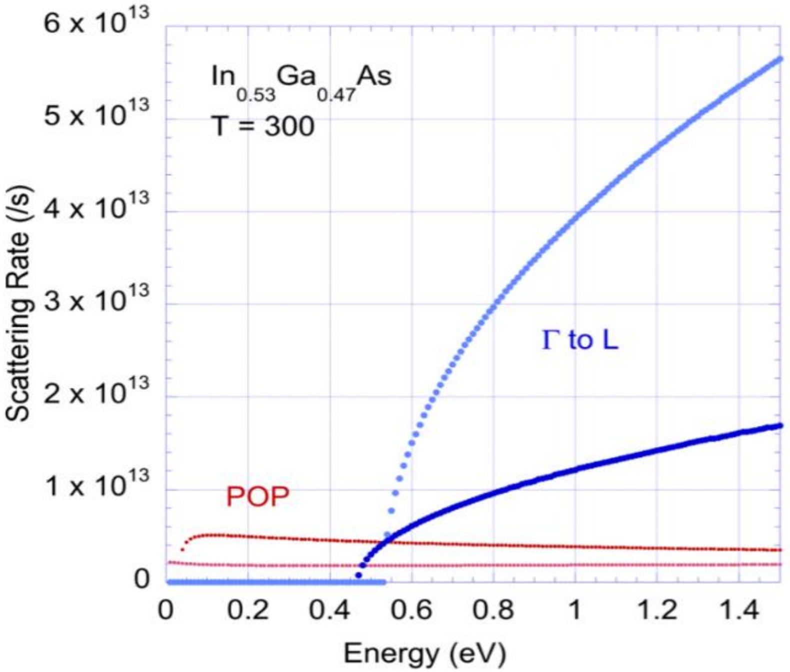
Guillemoles, J., Kirchartz, T., Cahen, D. *et al.* Guide for the perplexed to the Shockley–Queisser model for solar cells. *Nat. Photonics* **13,** 501–505 (2019). https://doi.org/10.1038/s41566-019-0479-2

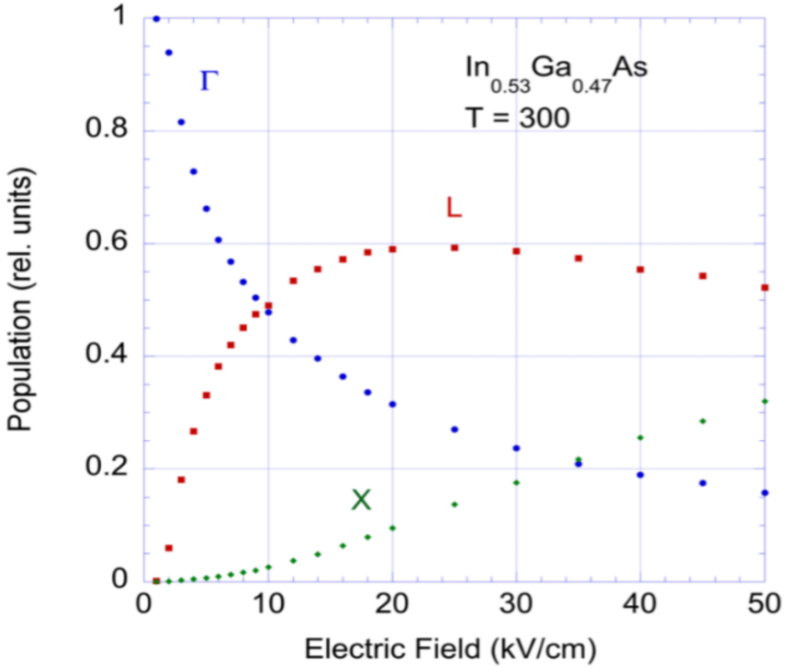
- Single gap solar cells are limited to ~30% efficiency
- Photons above the bandgap will generate “hot carriers” that swiftly thermalize
- A hot carrier solar cell addresses *thermalization loss* by extracting those high energy electrons

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).

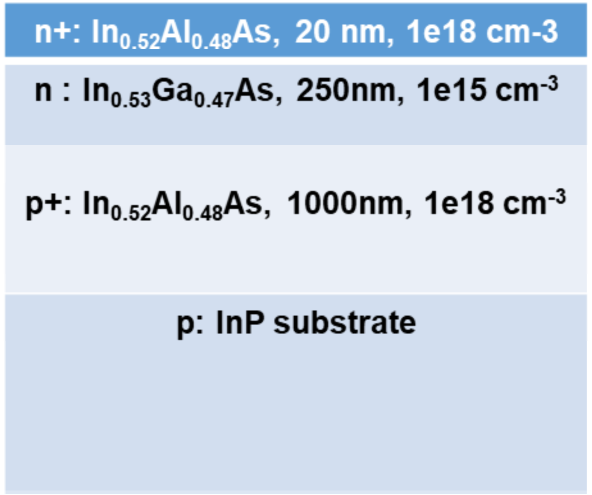


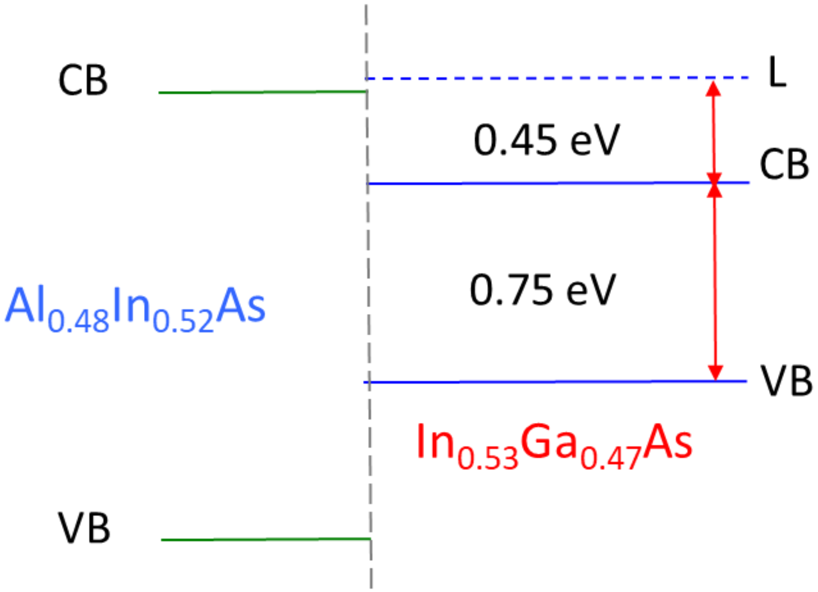




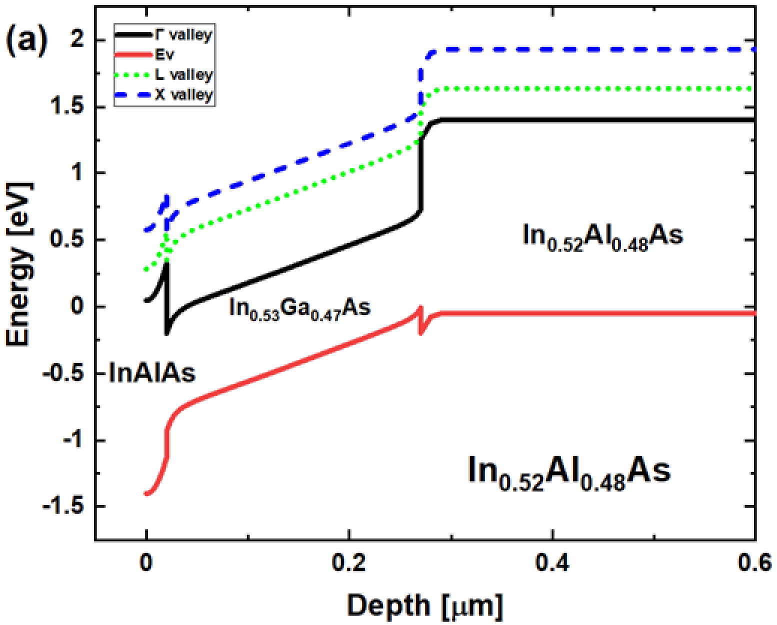
- High energy electrons: Intervalley scattering
- Low energy electrons: The Gunn Effect
- Transfer, store, and extract via upper valleys!

Device Structure





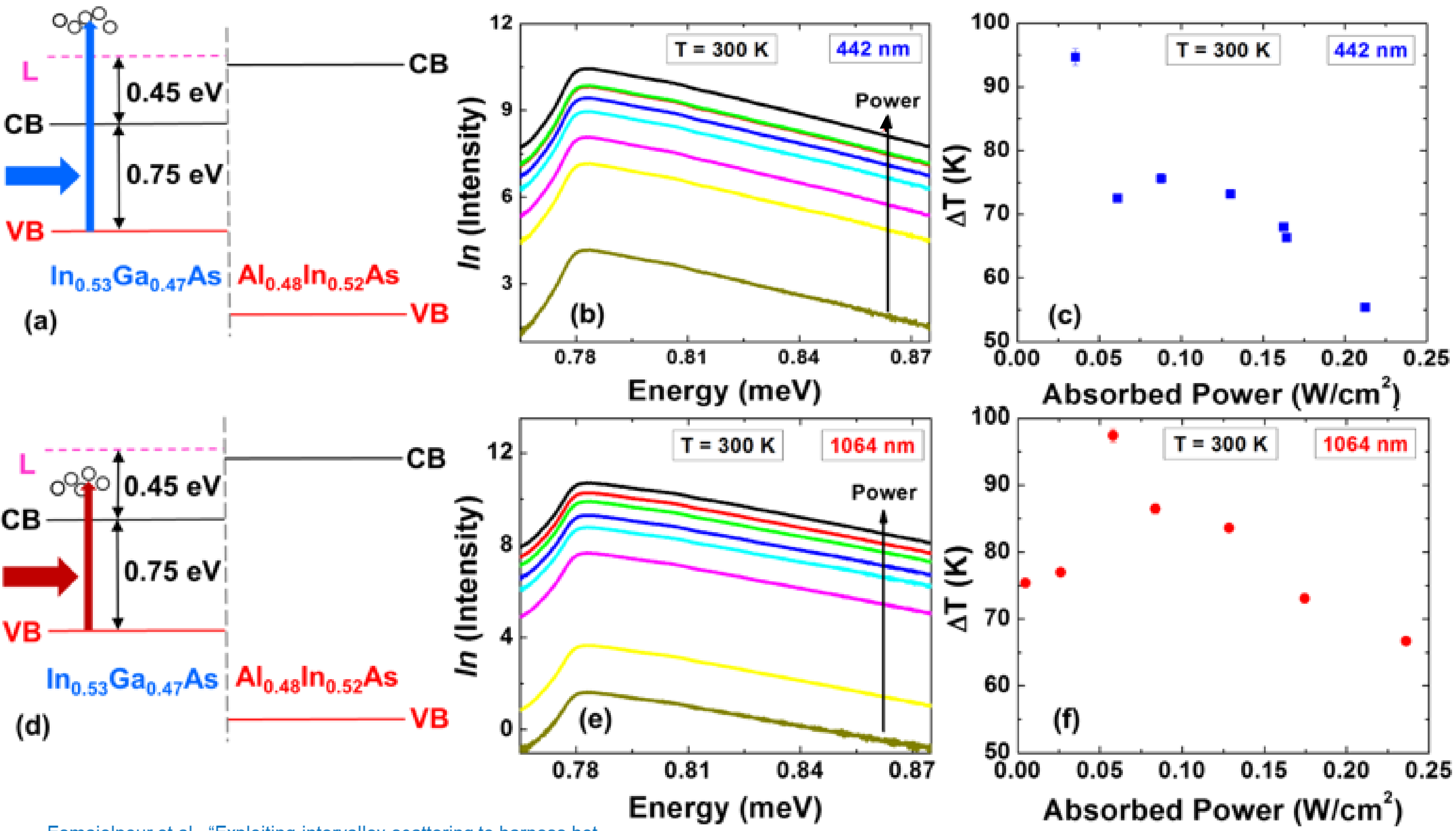
- Need a resonant barrier material with InGaAs, and an absorber with both a bandgap and an L valley in the solar spectrum.

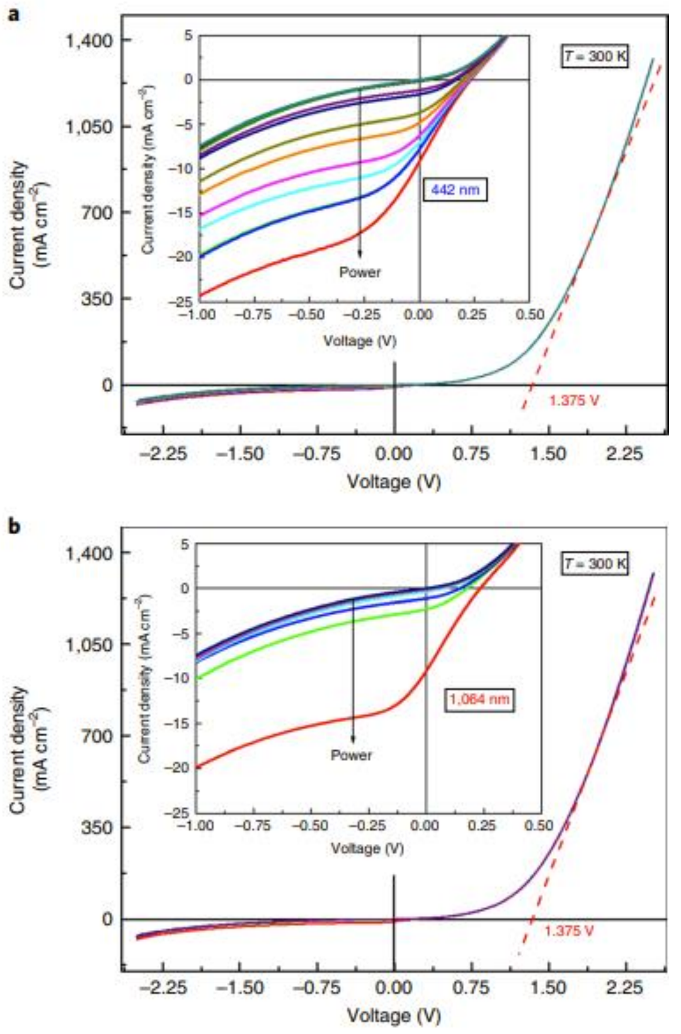


Esmaielpour et al., "Exploiting intervalley scattering to harness hot carriers in III–V solar cells," Nature Energy **5,** 336-343 (2020).

Hot Carrier Effects: Evidence for Intervalley Scattering

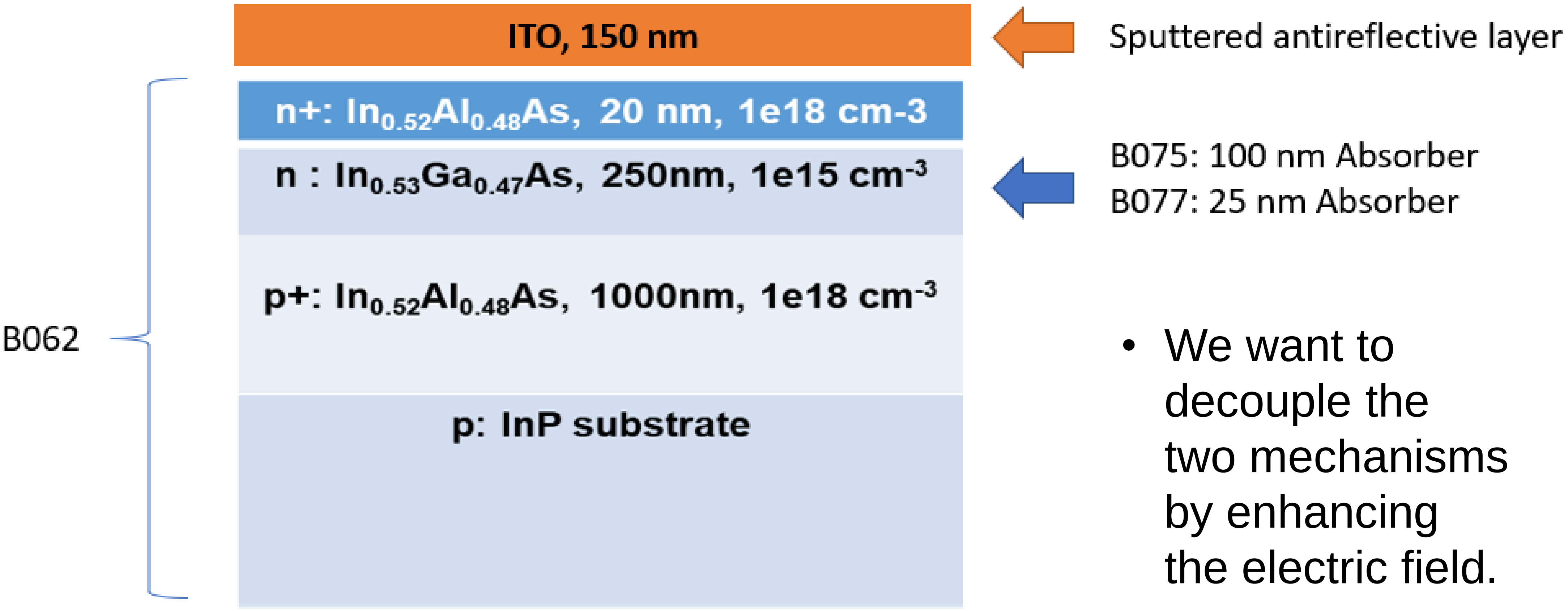
$$I(E) = \varepsilon(E) \cdot \exp\left[\frac{-E}{k_B T_c}\right]$$





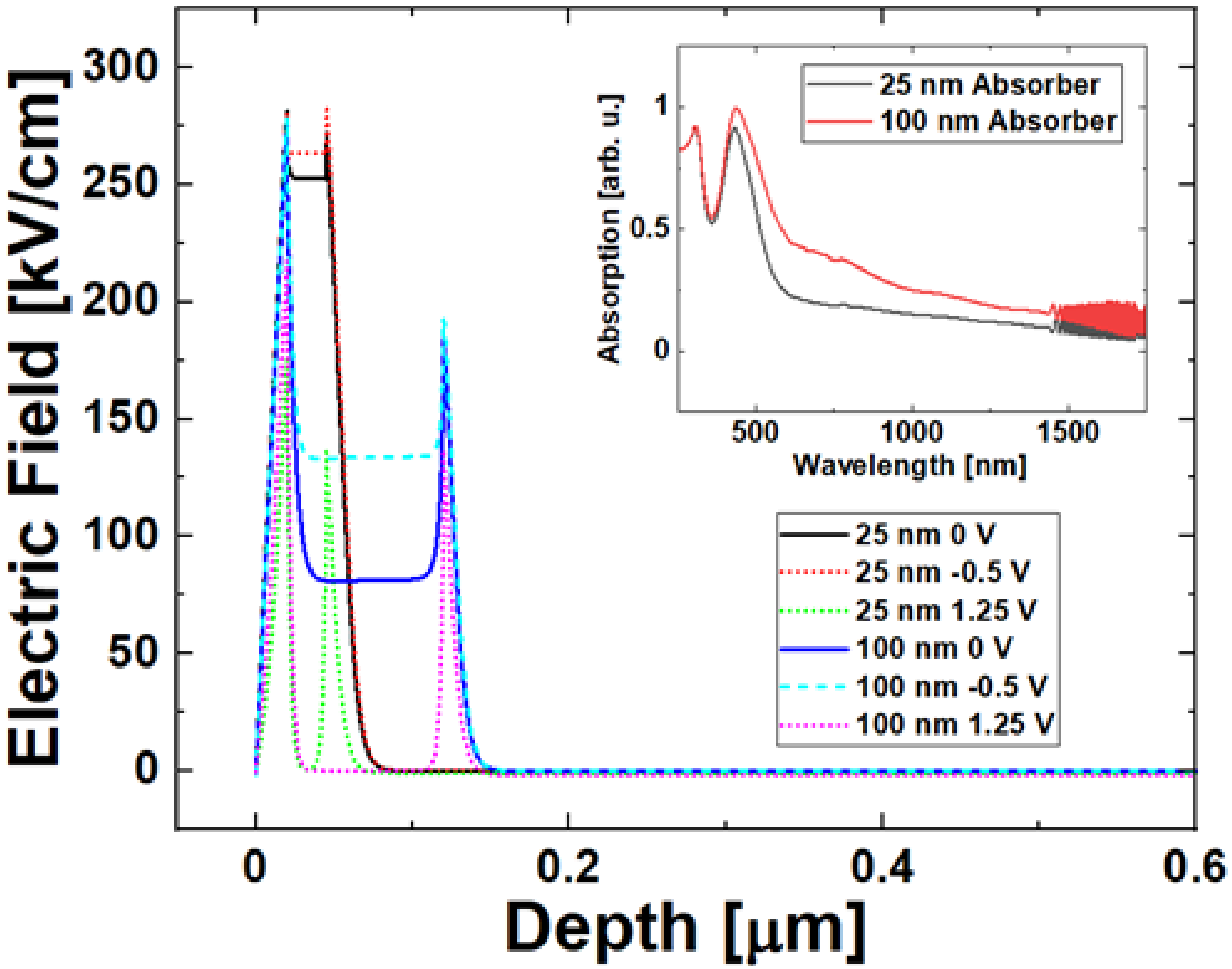
Esmaielpour et al., "Exploiting intervalley scattering to harness hot carriers in III–V solar cells," Nature Energy **5,** 336-343 (2020).

New Device Structure



- We want to decouple the two mechanisms by enhancing the electric field.

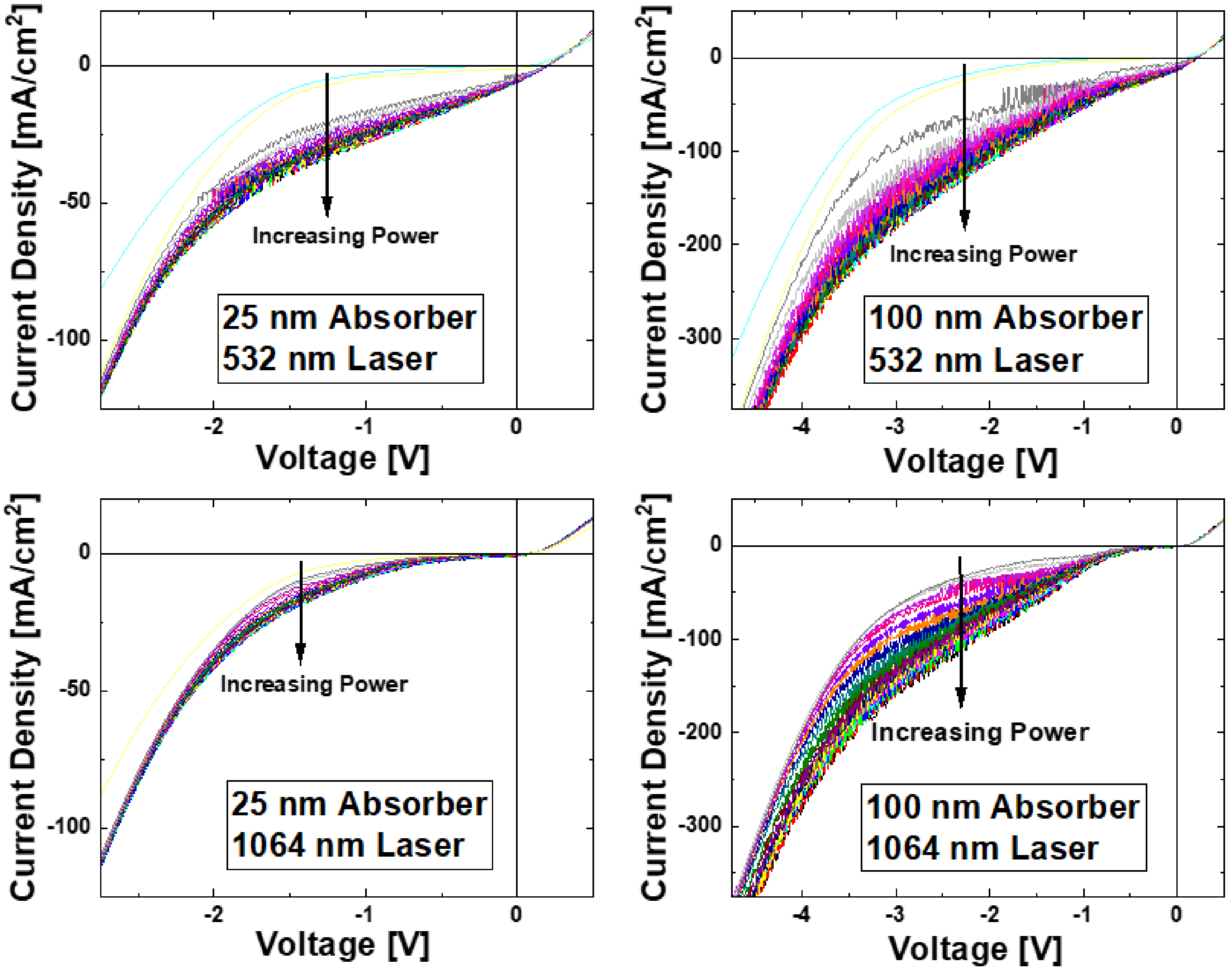
Electric Field Effects



- Change the InGaAs thickness to change the inherent electric field strength and absorptivity.
- Field is an internal field from the doping profile. Applying a bias modifies the field strength in the middle of the absorber.
- Spikes at interface are robust, and large enough to cause the Gunn Effect.

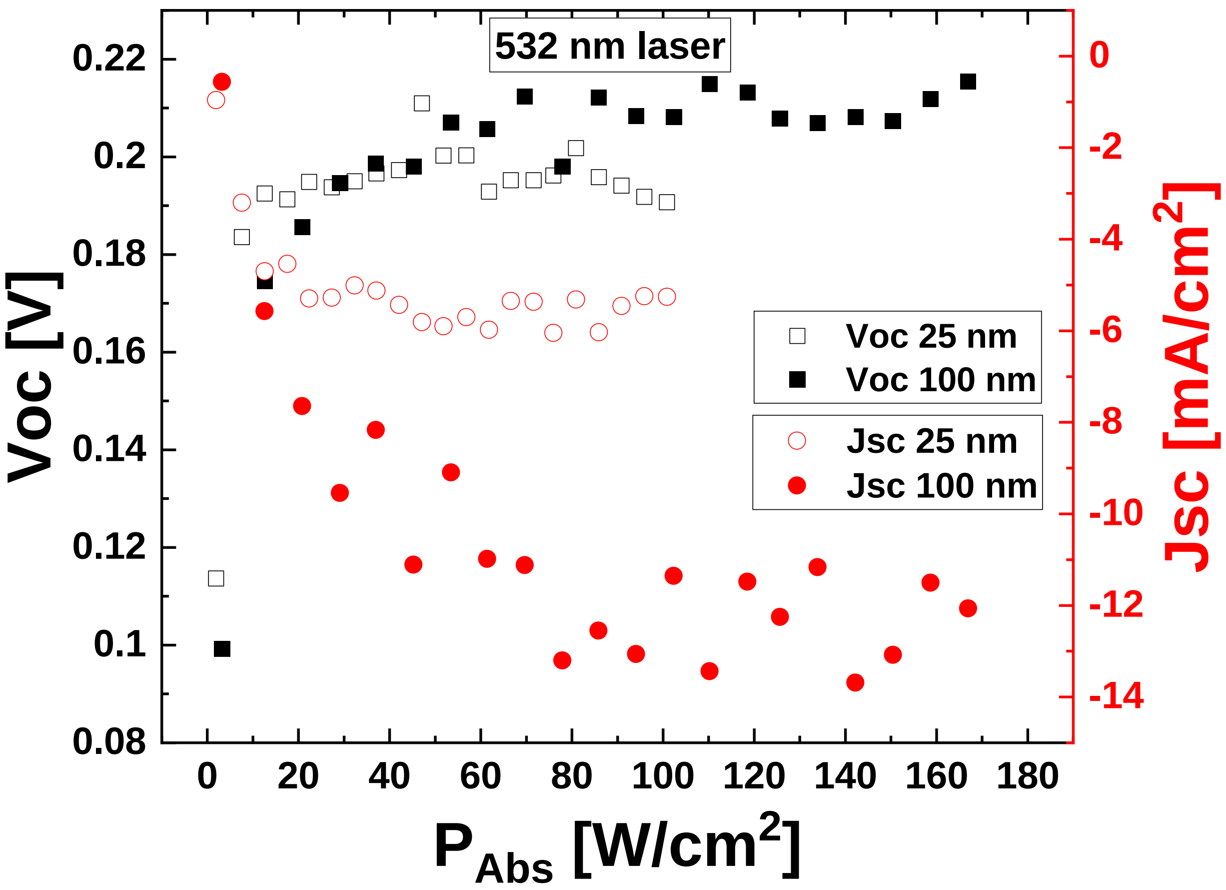
Dorman et al., IEEE JPV, pending.

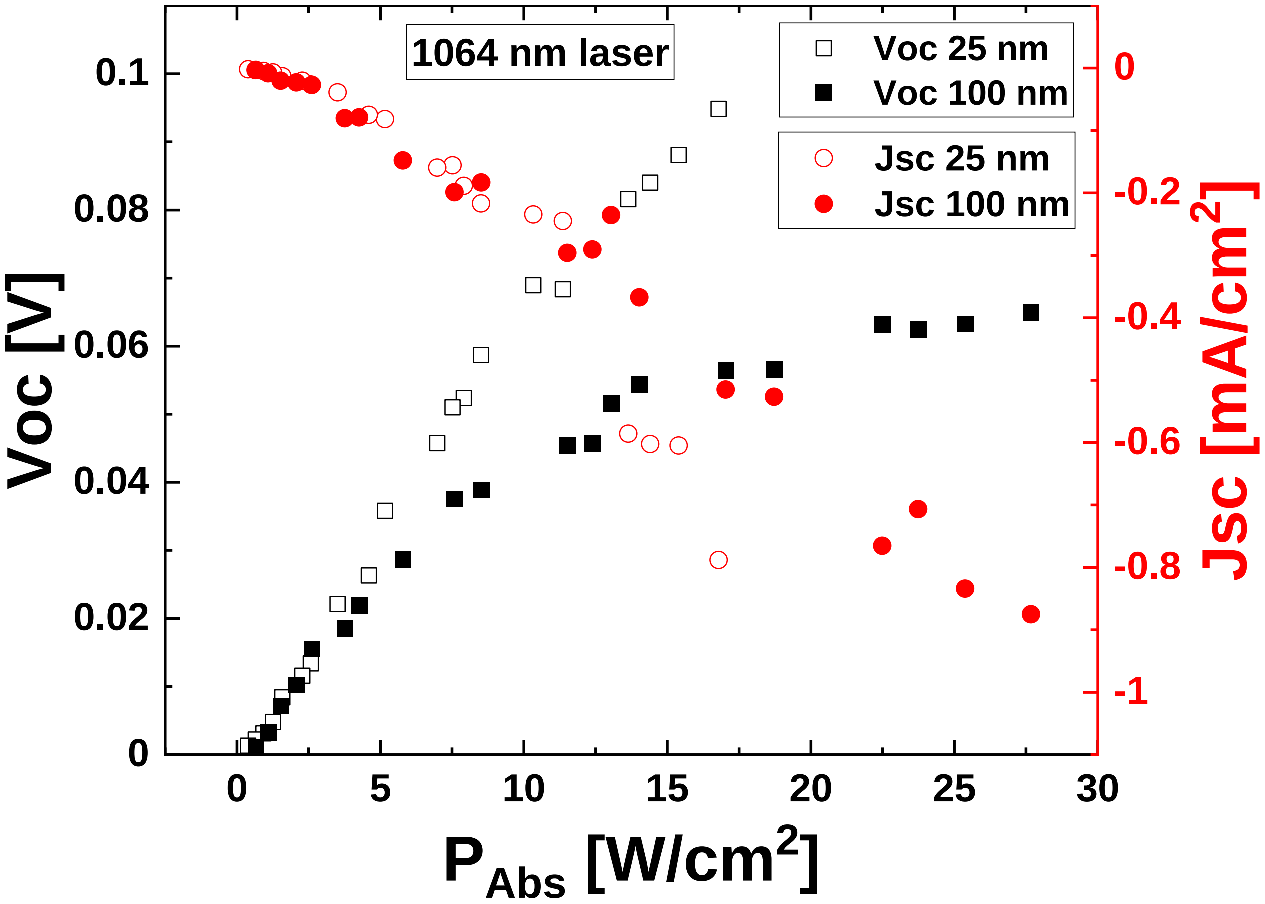
Current Density-Voltage Measurements



Dorman et al., IEEE JPV, pending.

Power Dependent PV Parameters

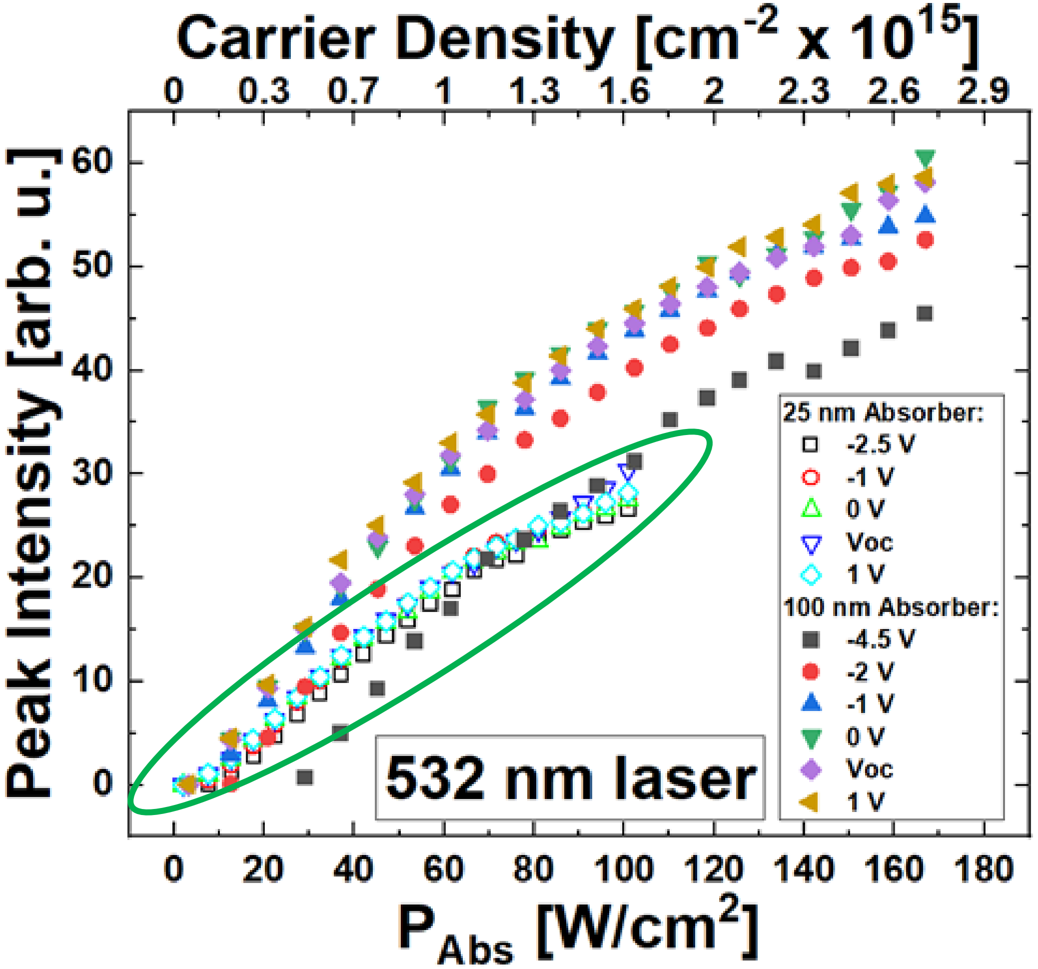


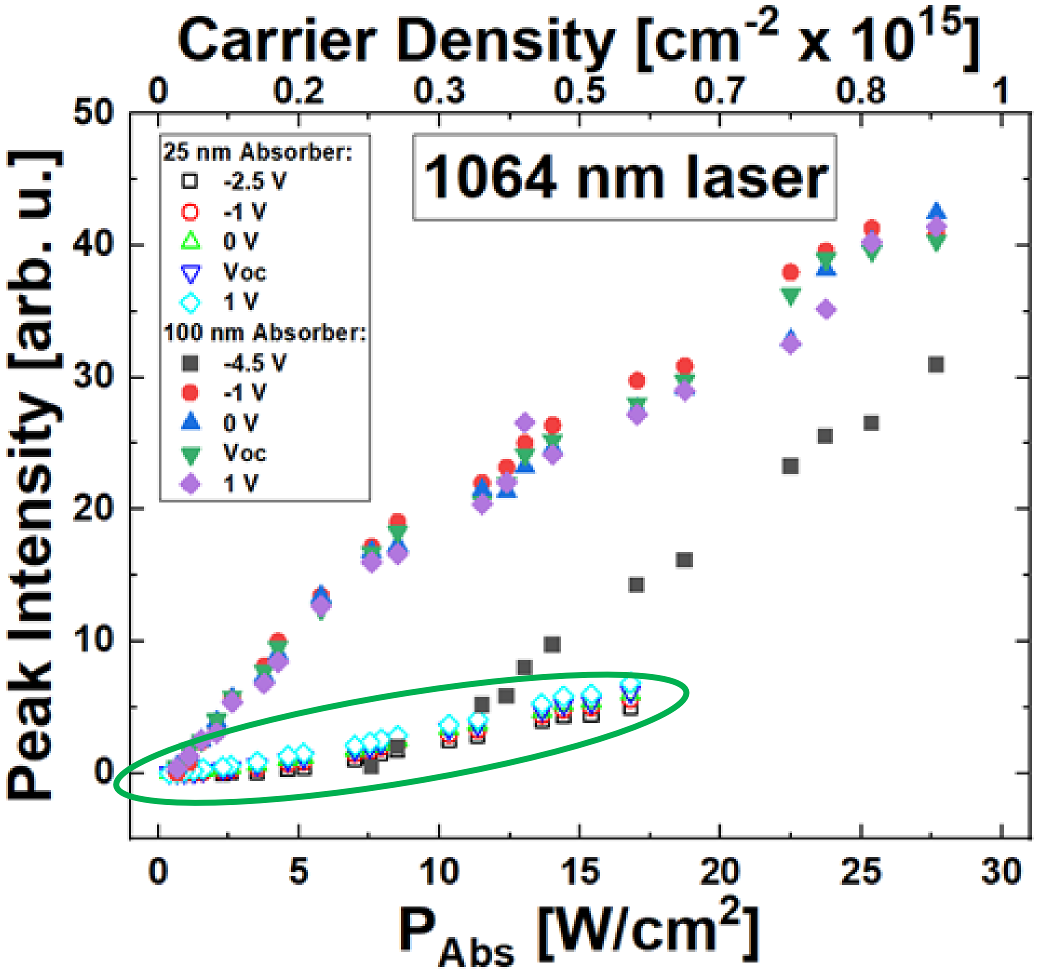


- Top barrier material limits Voc and Jsc.
- Electric field enhancement of extraction at high powers, more effective over a larger distance.

Dorman et al., IEEE JPV, pending.

Bias Dependent Photoluminescence

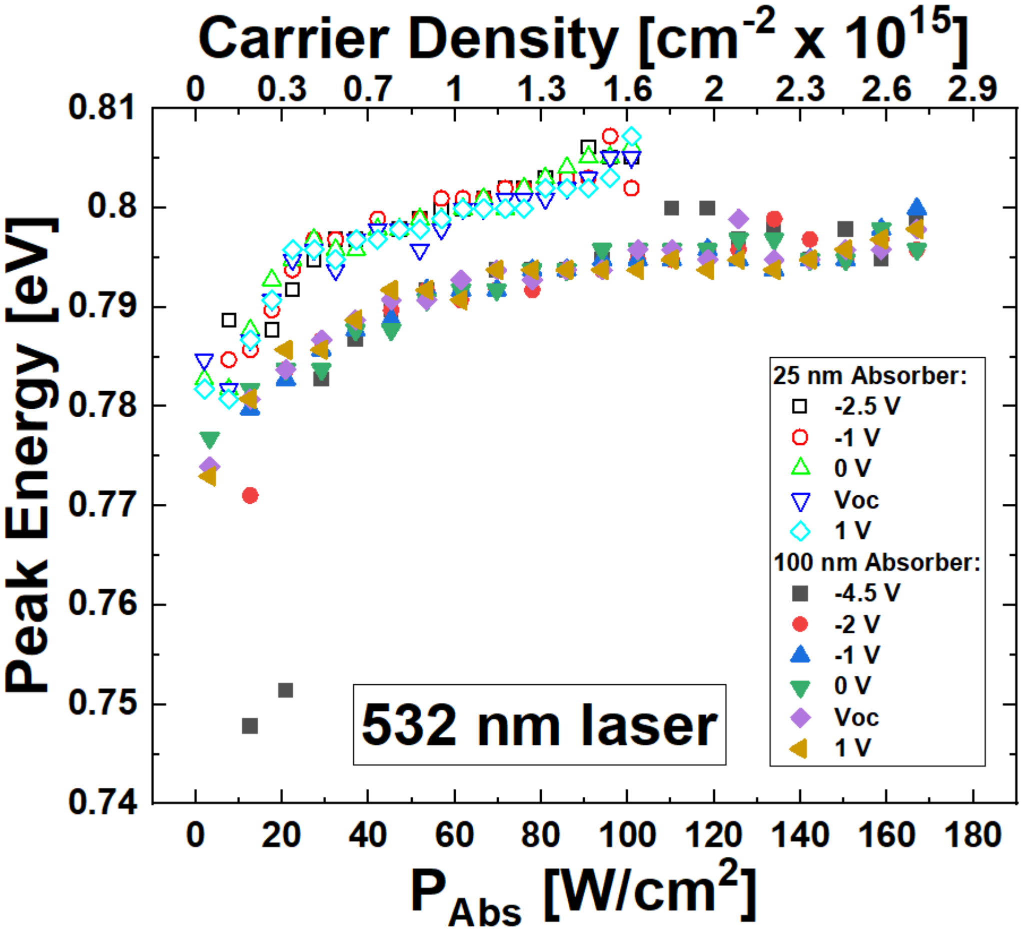


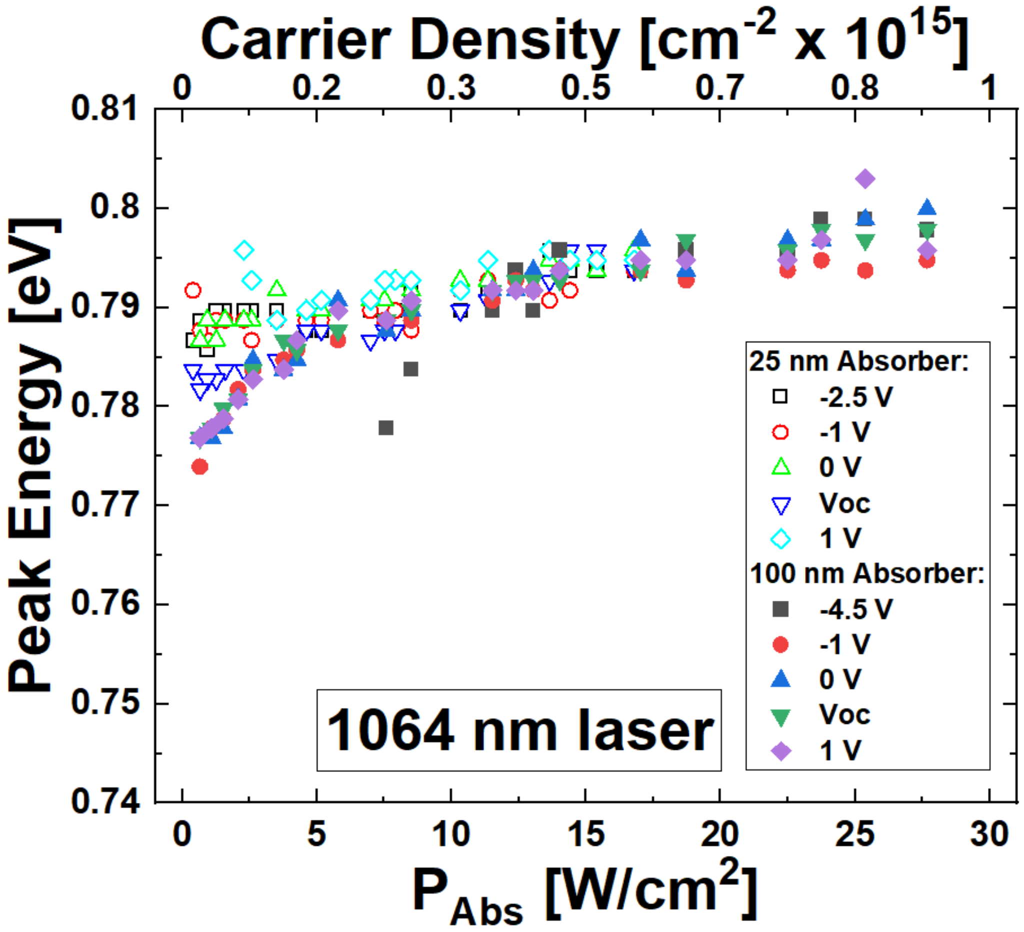


- Carriers that extract successfully do not recombine to emit photons, so the bias dependence is strong in the intensity.

Dorman et al., IEEE JPV, pending.

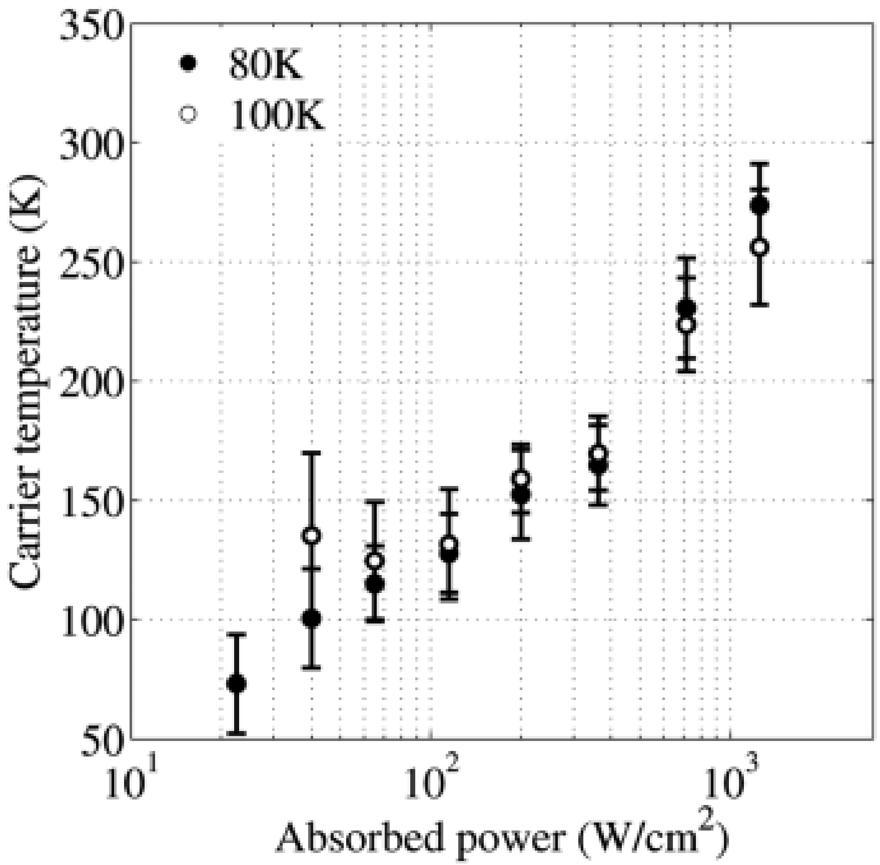
Bias Dependent PL Energy

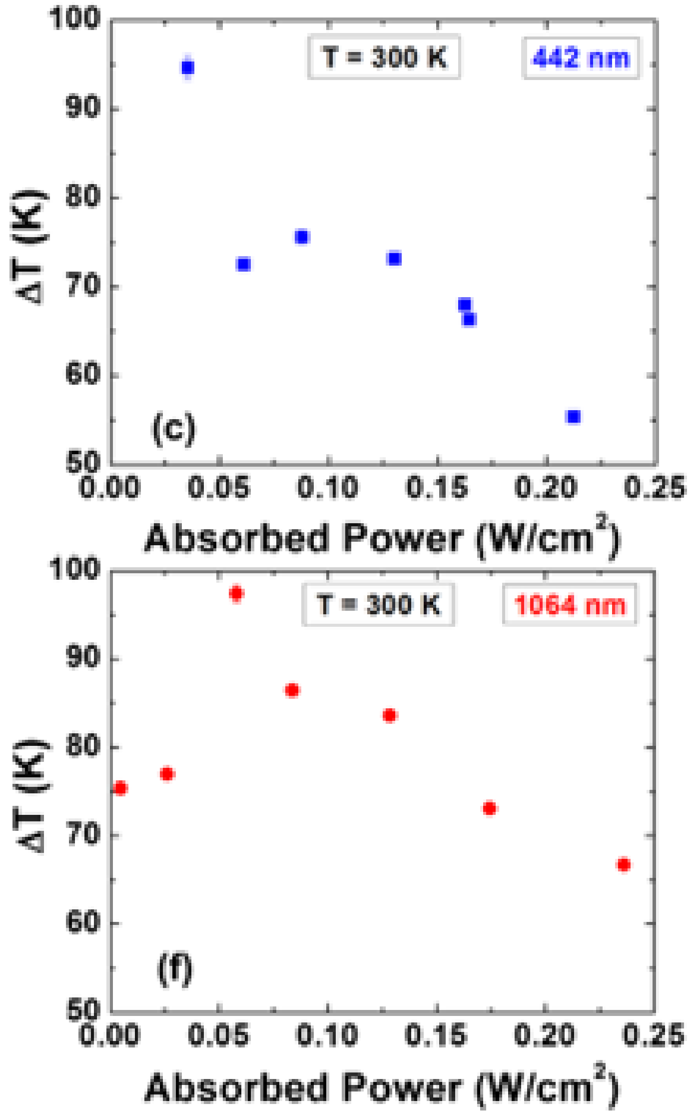




- Blueshifts, unlikely to be a lattice heating effect due to laser illumination.
- Could be enhanced by fields formed by increasing carrier densities at the interface, but not very bias dependent.
- Most likely a result of modified carrier distribution! Can analyze ΔT…

Dorman et al., IEEE JPV, pending.





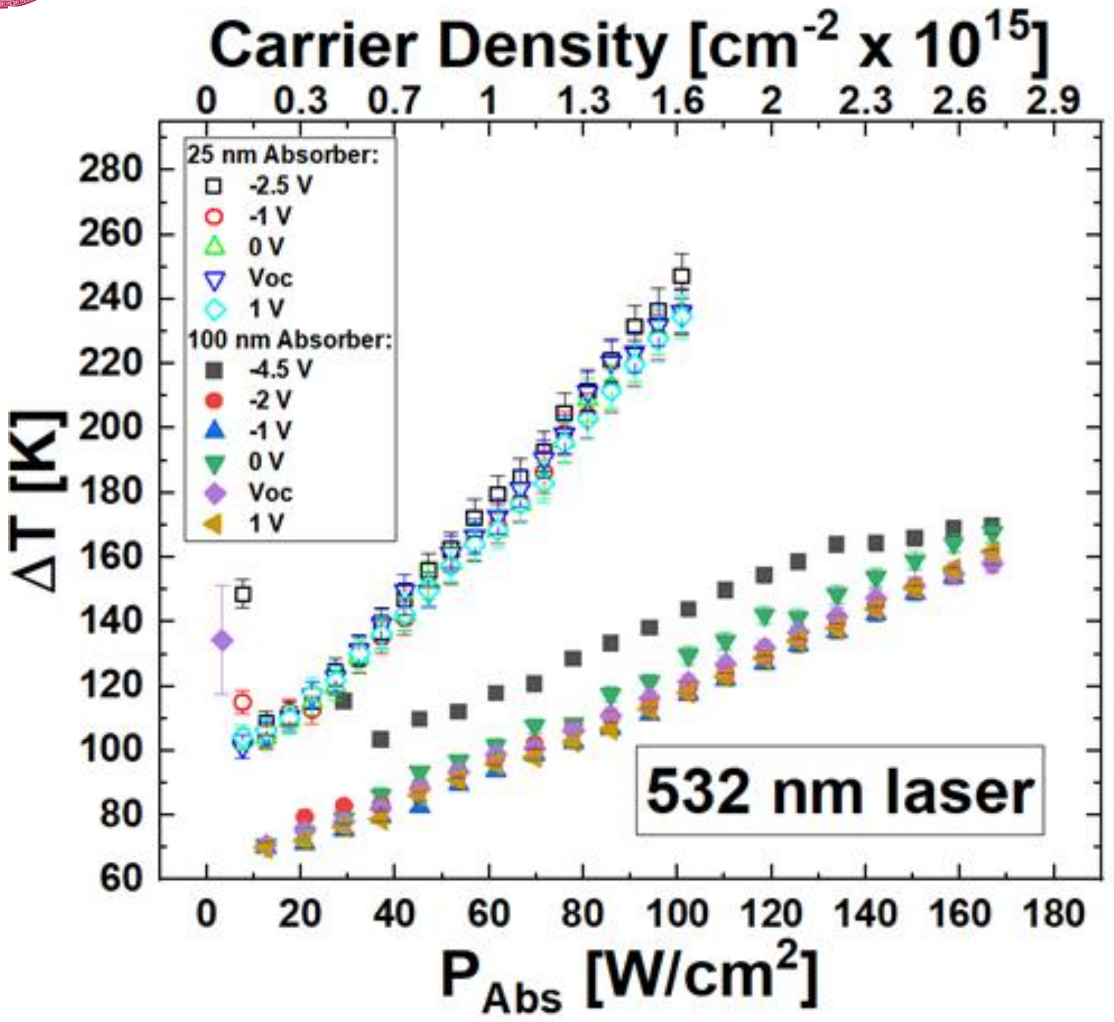
- Phonon bottleneck:
  - Power dependent
  - Turns off at low power

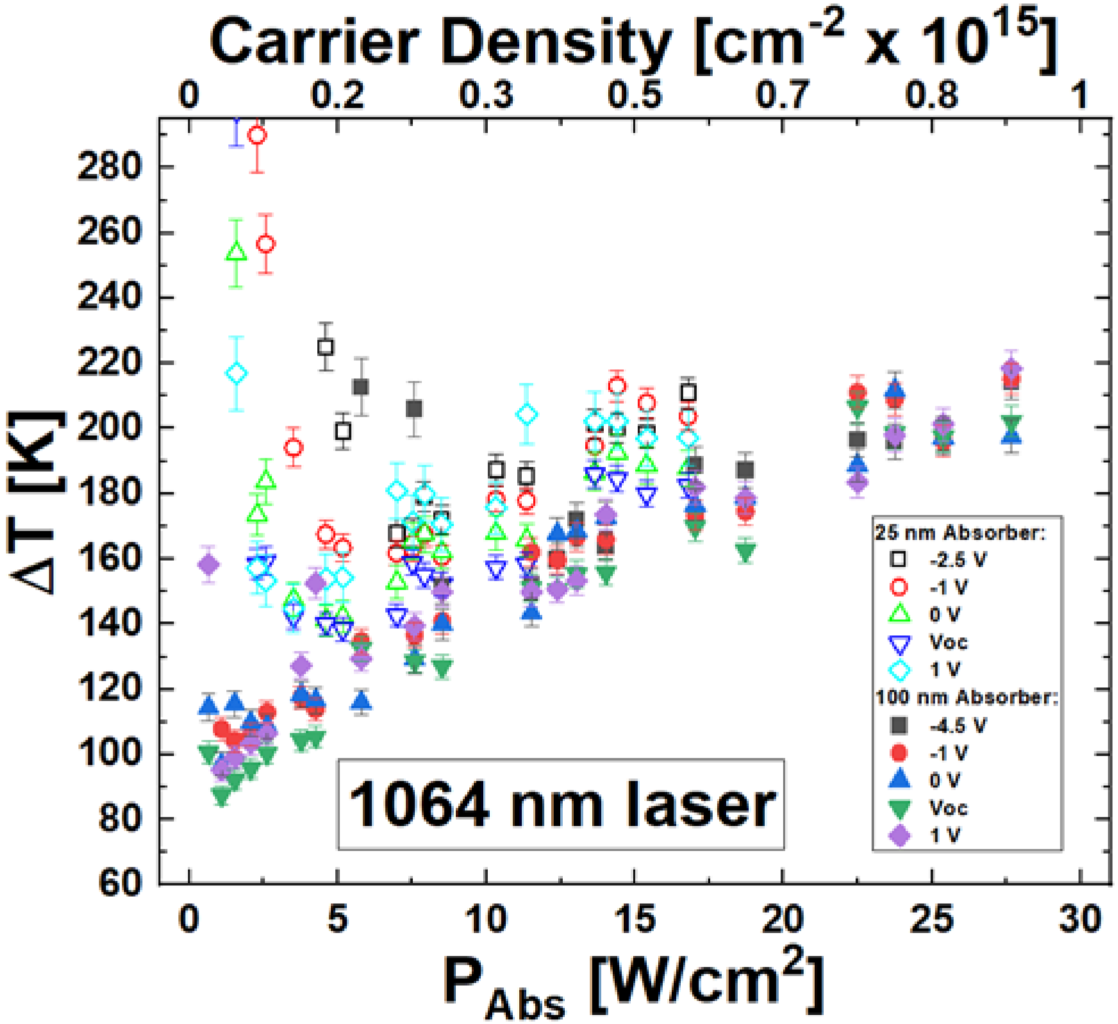
Le Bris et al., Energy Environ. Sci. vol. 5, pp. 6225–6232, 2012.

- Intervalley behavior:
  - Robust at low powers

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

Bias Dependent Carrier Temperatures





- Temperature difference from lattice non-zero at low power, increased at higher field strength.
- Bottleneck-type temperature enhancement with power, stronger dependence at high field.

Dorman et al., IEEE JPV, pending.

Conclusions and Acknowledgments

- The InGaAs heterostructure once again proves a robust system for maintaining a hot carrier population due to the intervalley properties, if limited in extraction.
- By altering the absorber thickness, the electric field inside the device is enhanced, resulting in power dependence akin to a more standard phonon bottleneck, but possessed of a nonzero base temperature.
- The enhancement of the electric field provides large benefits: both an increased base hot carrier temperature and the role it plays in accelerating low energy carriers to the upper valleys.

This work is made possible by financial support from the **Department of Energy EPSCoR Program and the Office of Basic Energy Sciences, Materials Science and Energy Division under Award No. #DE-SC0019384.** The GENxplor MBE system was acquired with support from **NSF Grant No. DMR-1229678**.

This work was performed under the umbrella of the **Oklahoma Photovoltaics Research Institute (OKPVRI)** and the **Center for Quantum Research and Technology (CQRT)** at the **University of Oklahoma**.