Hot Carrier Solar Cells based on Inter-Valley Phonon Scattering: A *Different* Approach Towards a Practical Solution

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- **Hot Carrier Solar Cells: Introduction, Current Status, State-of-the Art**
- **The Role of Inter Valley and LO Phonons in Hot Carrier Thermalization**
- **Proof of Principle Demonstration of Valley Photovoltaics**

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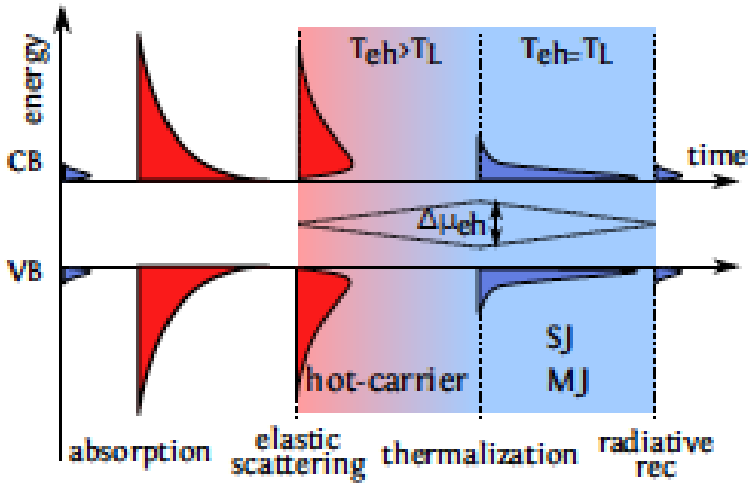
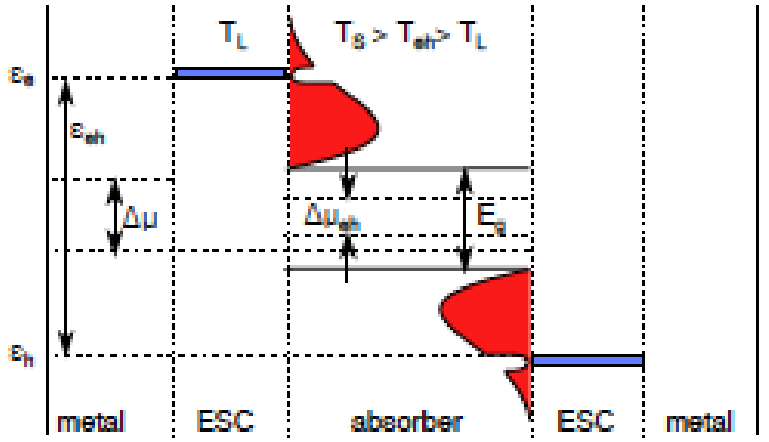
Hot Carrier Losses and Solar Cells



Green, Third generation photovoltaics, p.70 Springer (2006)

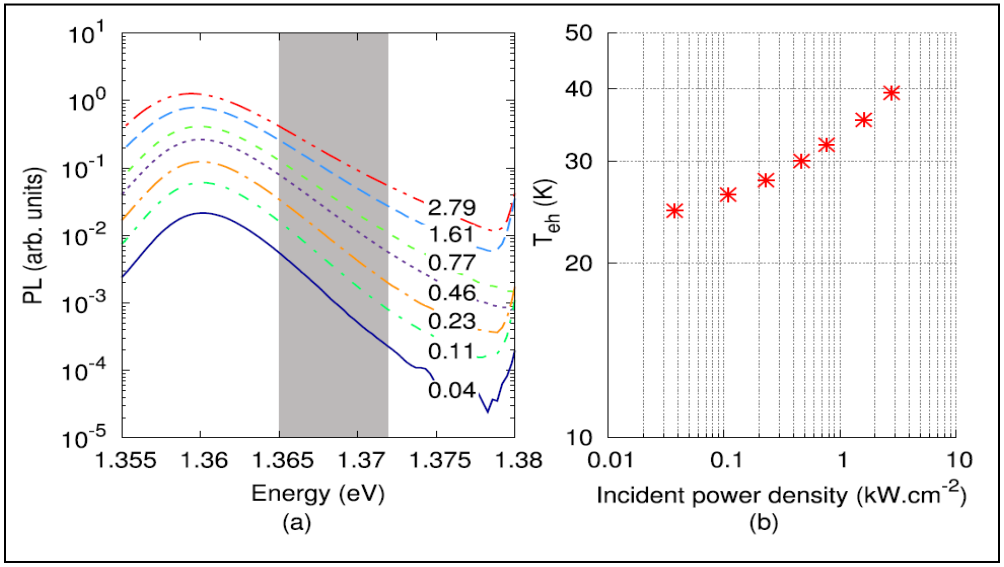


Wurfel, Sol. Energ. Mat. Sol. C., 46, p.43 (1997)

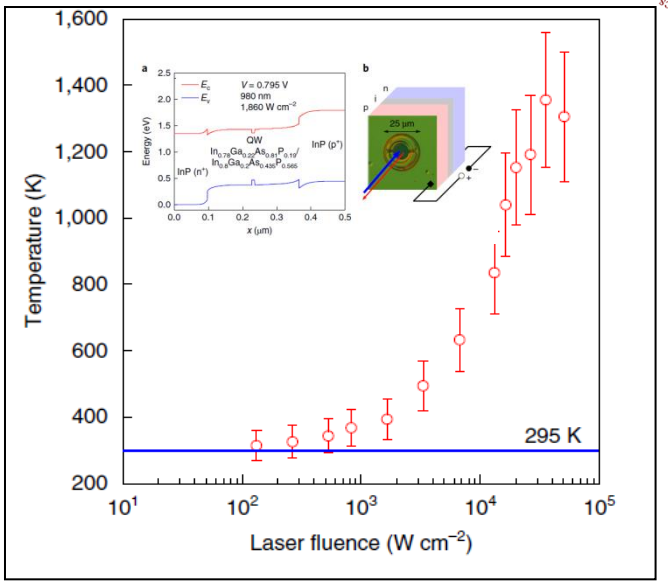
- "Hot carriers" rapidly transfer energy to the lattice – *thermalization*
- Rapid extraction of higher energy carriers via energy selective contacts has potential to increase power conversion:

- selective energy extraction
- inhibited electron-phonon relaxation pathways
- phonon bottleneck

Evidence of Hot-Carrier Effects in QWSC



Hirst & Ekins-Daukes. Appl. Phys. Lett. **104**, 231115 (2014)



Nguyen, Lombez, Guillemoles *et al.*
Nature Energy **3**, 231115 (2018)

Maxwell-Boltzmann like distribution of carriers:

$$I(PL) \propto \exp\left(-\frac{h\nu}{k_B T_H}\right)$$

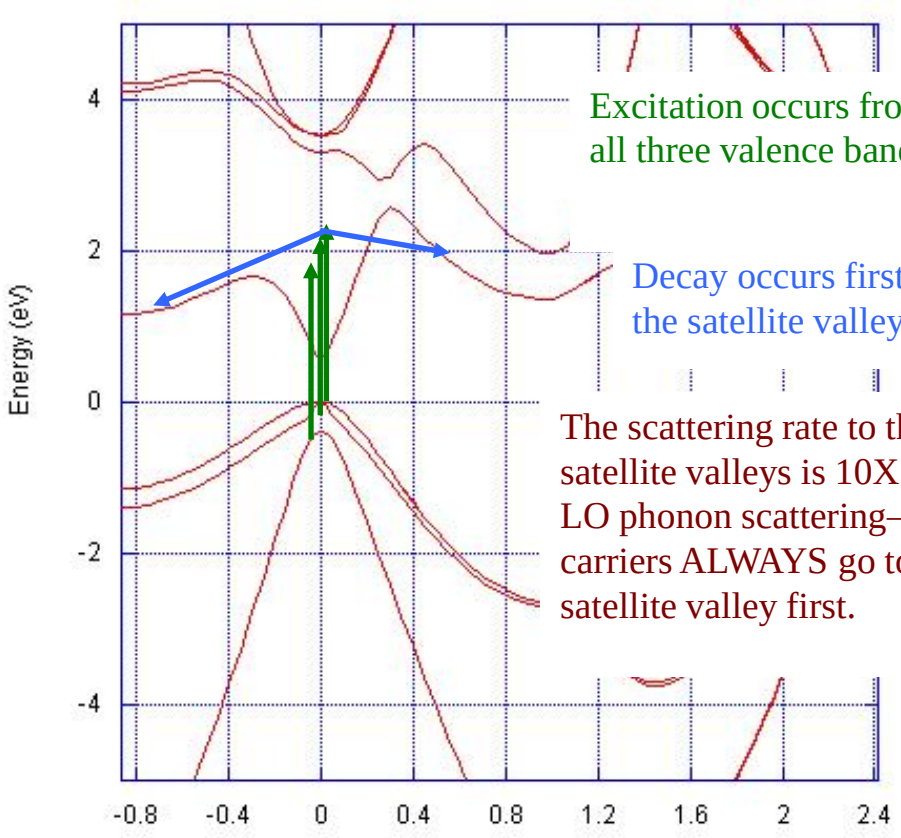
- Lasher & Stern, *Phys. Rev.* ***133****, A553 (1964)*
- De Vos & Pauwels, *Appl. Phys.* ***25****, 119 (1981)*
- P Wurfel, *J. Phys. C: Solid State Phys.* **15** 3967 (1982)

Proof of principle systems

- **Very high power excitation**
- **Monochromatic illumination**
- **Non-optimum architecture**

Hot Carrier Thermalization: LO vs IV Phonons*

Consider a typical direct gap III-V



- Scattering via inter valley phonons >>> LO emission
- Hot carriers created optically and with high electron fields
- Effects important in THz devices (InAs HEMTs)

J Shah et al, IEEE Q. Elect. 22, 1728 (1986)

Clady, Koenig, Ekins-Daukes, Conibeer, Green *et al*. Prog. in PV. 20, 82 (2012)

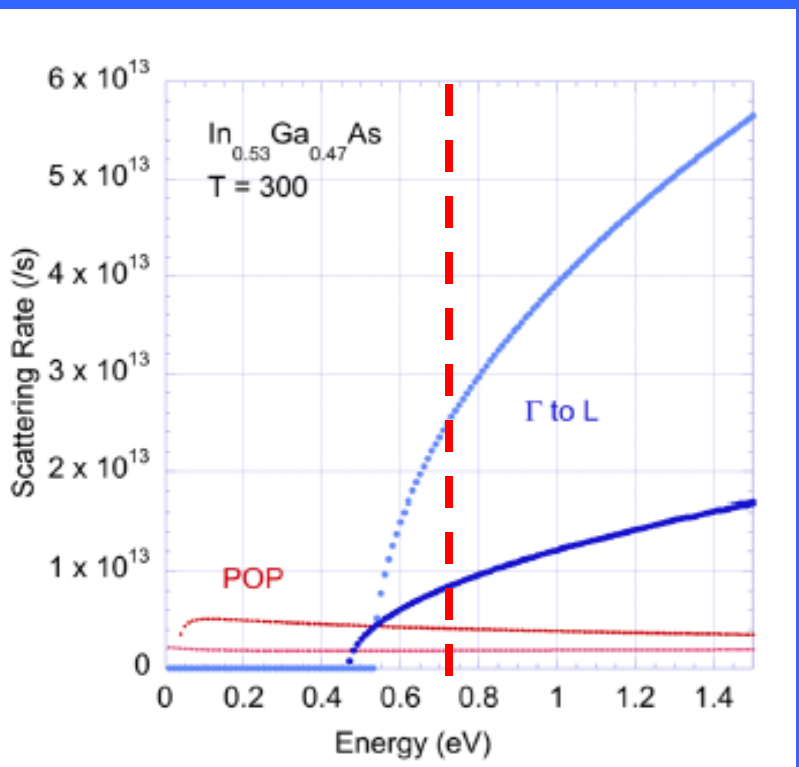
"Progress Toward Realization of the Hot Carrier Solar Cell" Special Issue Semi. Sci. Tech (2019)

*D. K. Ferry SST 34 (2019)

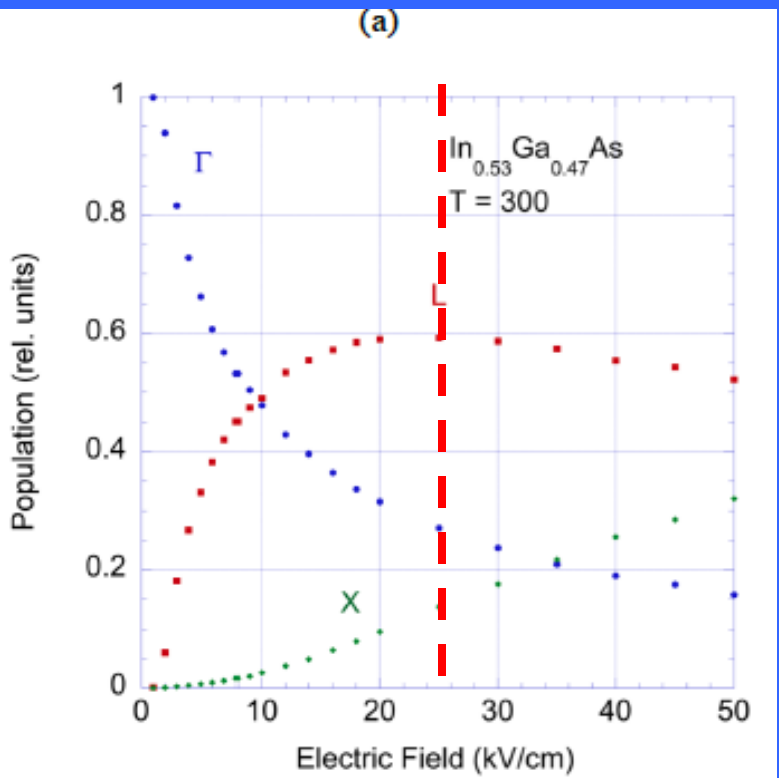
V. R. Whiteside, I. R. Sellers, D. K. Ferry *et al* . SST (2019)

Hot Carrier Generation:

Optical Excitation



E- Field *Acceleration*



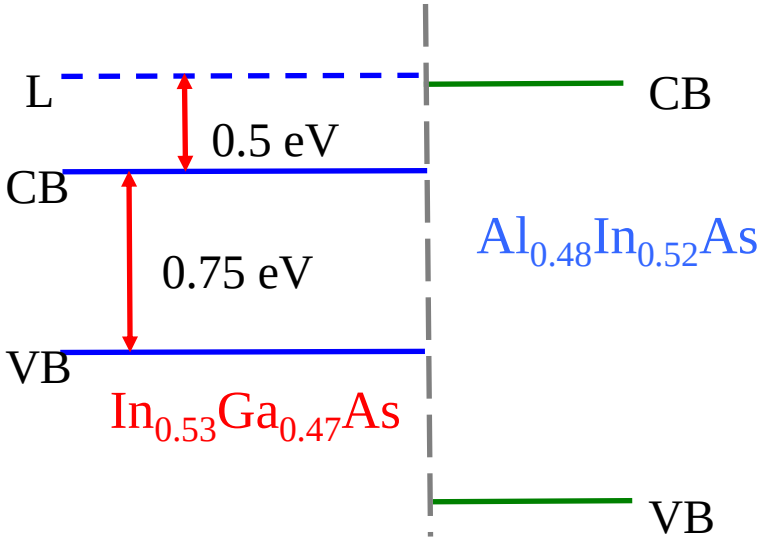
*D. K. Ferry Semi. Sci. Technology **34** (2019): 044001

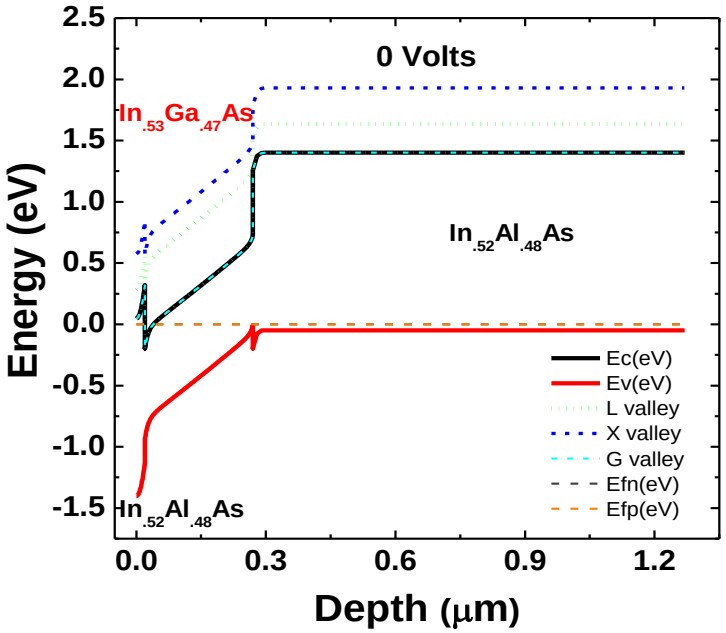
Can we invoke both effects to produce a practical hot carrier solar cell?

Hot Carrier Solar Cell based on IV Scattering

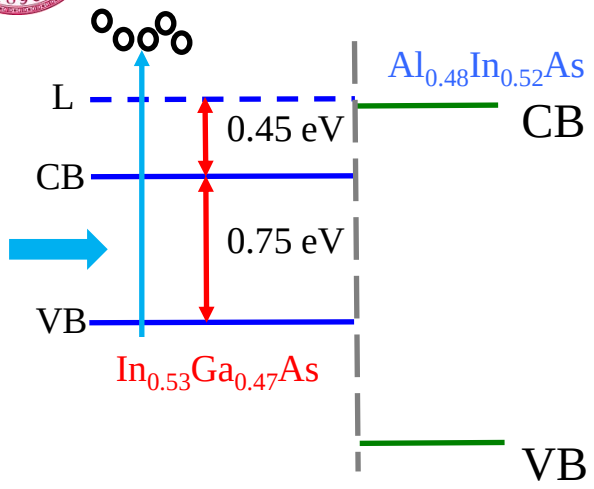
Requirements……

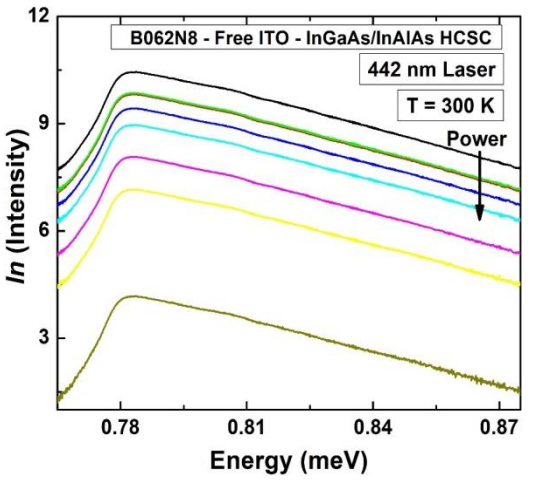
- Primary absorber matched to solar spectrum
- Relatively thin direct bandgap and lightly doped.
- High energy barrier/selection contact with appropriate valley degeneracy
- Traditional materials/established technologies:
  - InAs/AlAsSb
  - AlInAs/AlAsSb
  - InGaAs/AlInAs

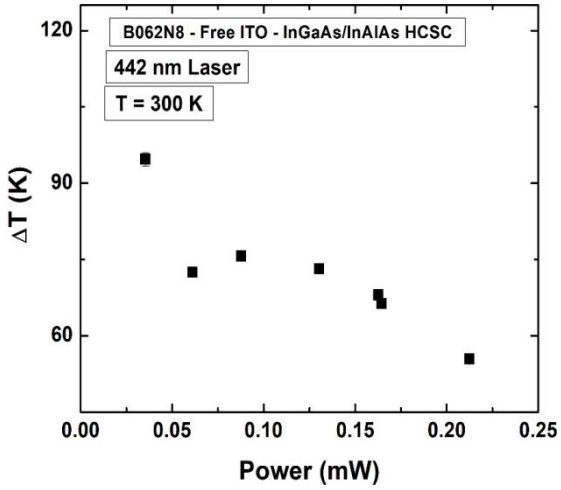


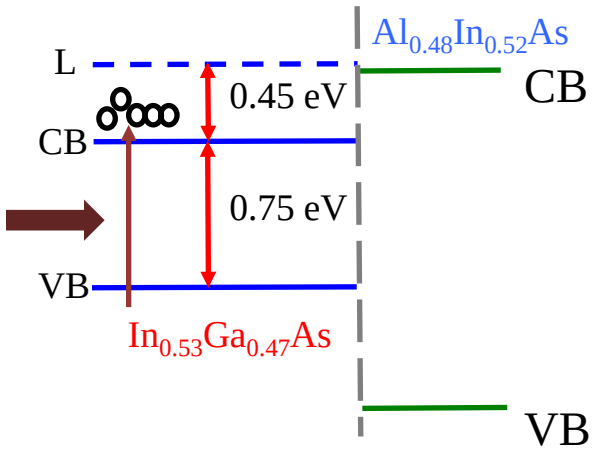


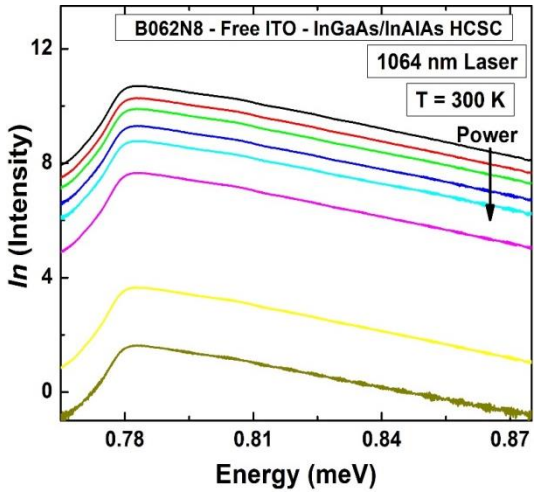
Evidence for Hot Carrier Generation/Scattering

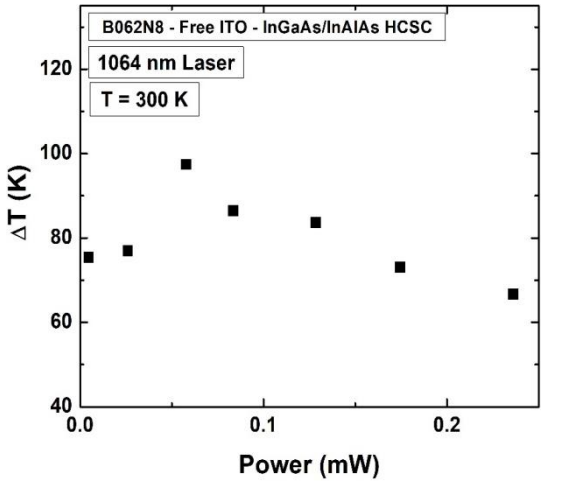






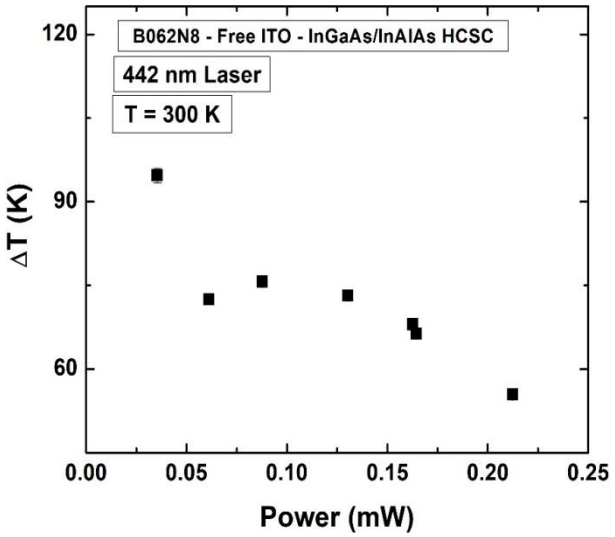


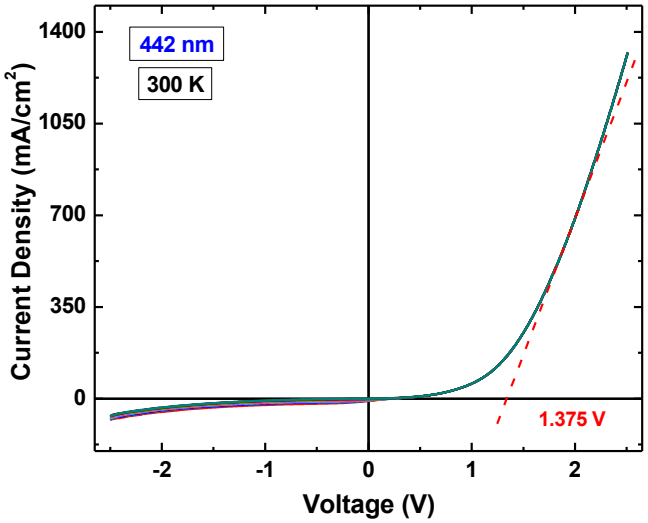


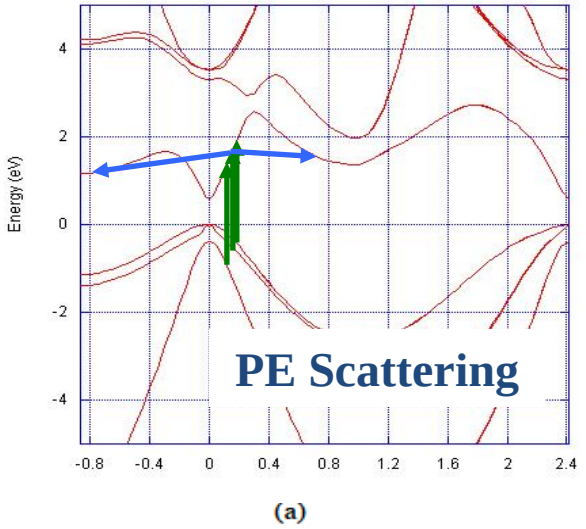


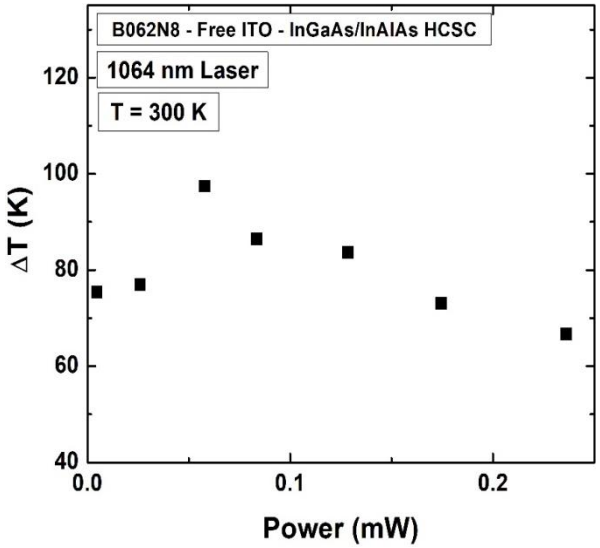
Evidence for hot carriers at low powers: at high *and* low excitation energy

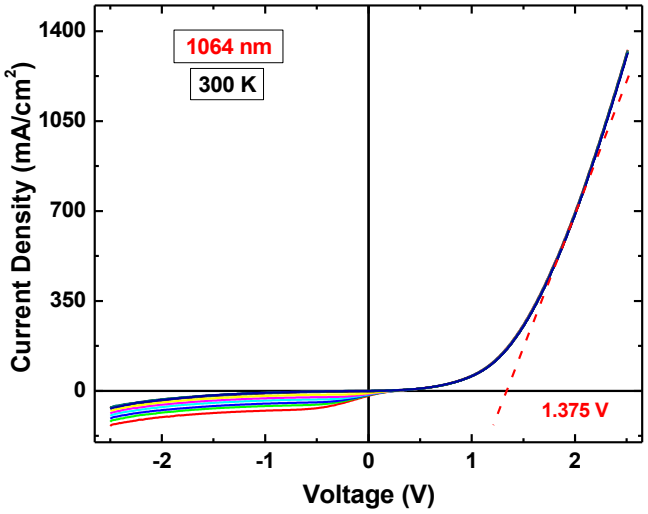
Inter-valley Hot Carrier Solar Cell: Hot carriers?

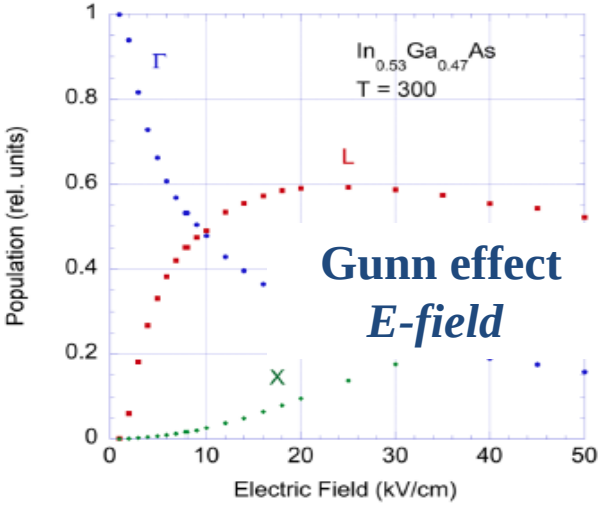




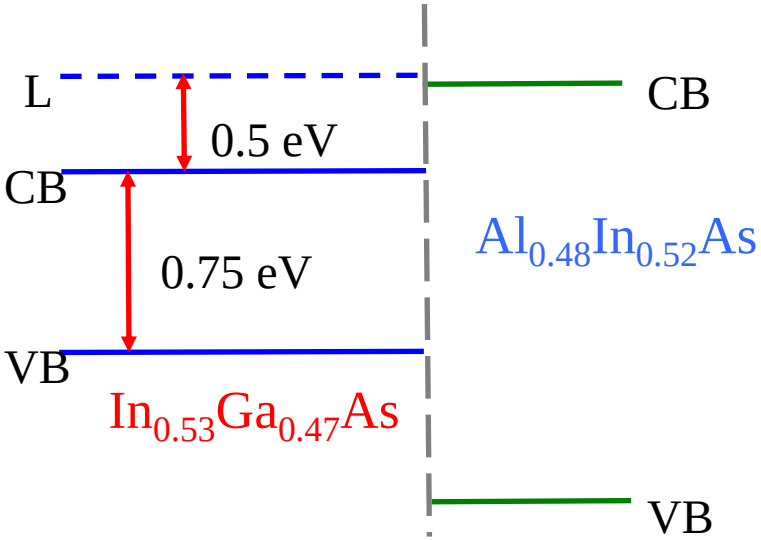


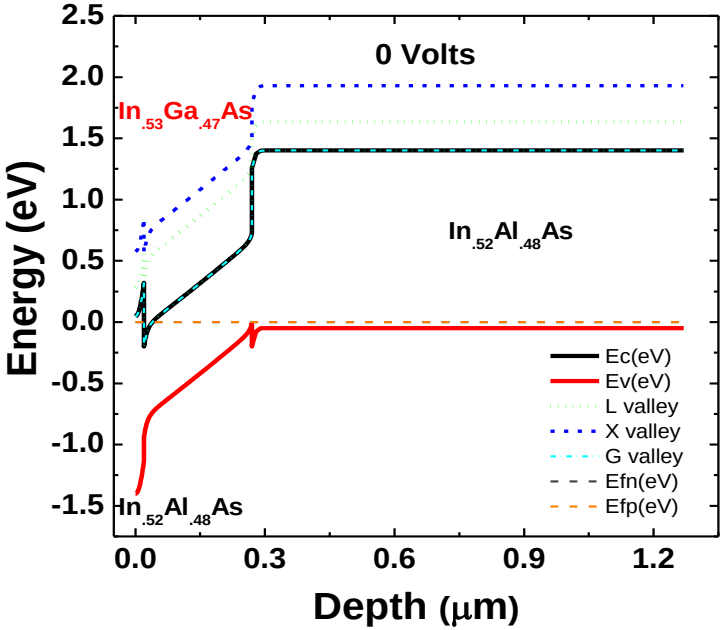


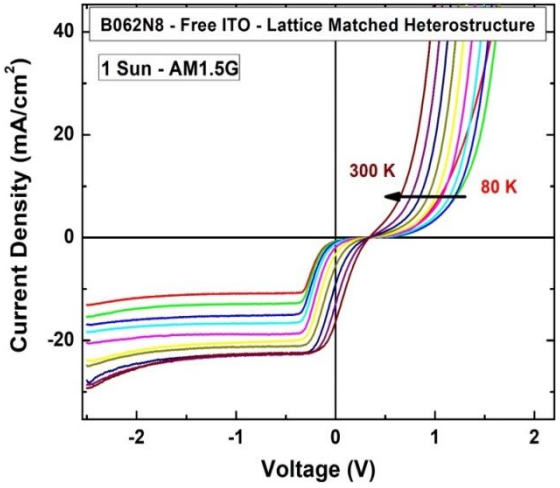


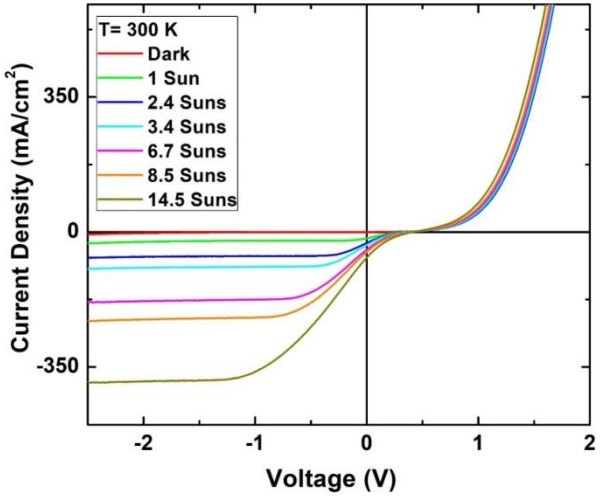


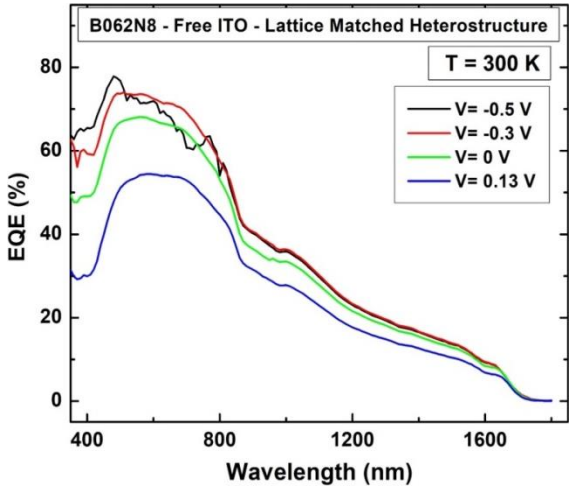
Inter-valley Hot Carrier Solar Cell: Experimental



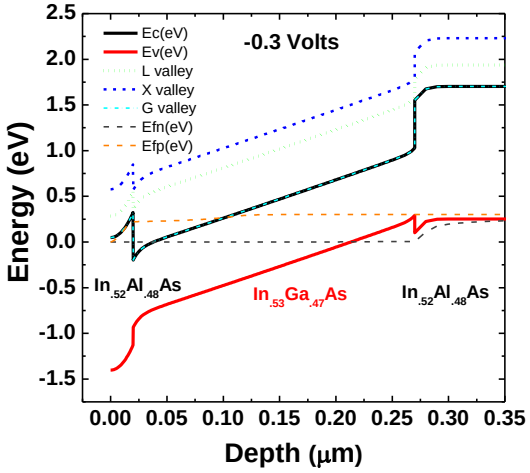


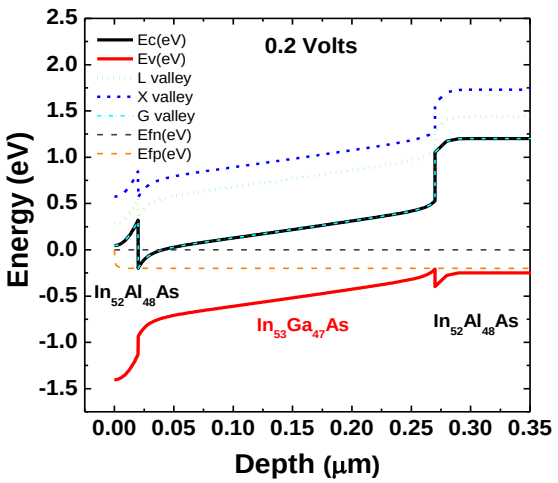


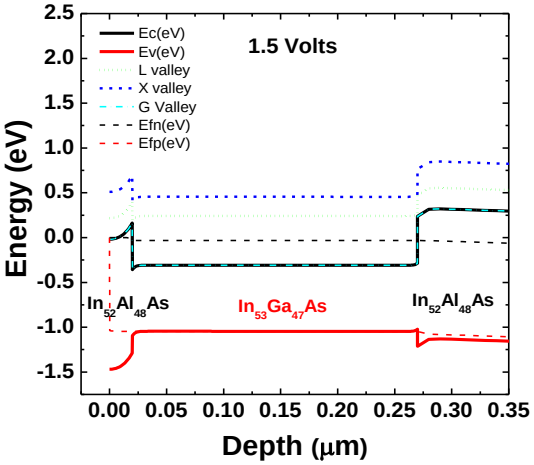


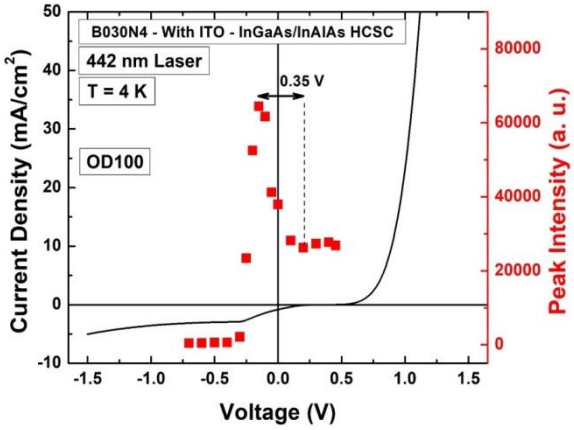


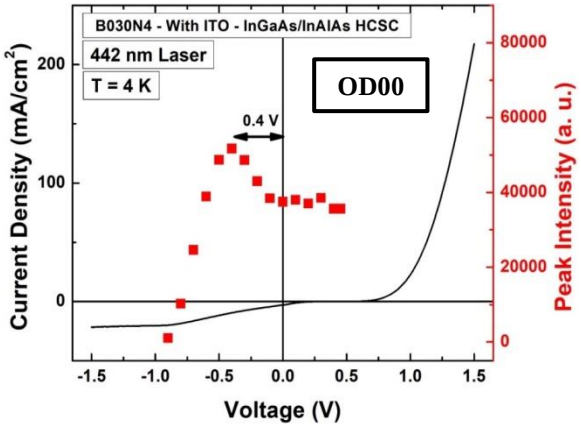
Origin of Carrier Localization/Inhibited Extraction

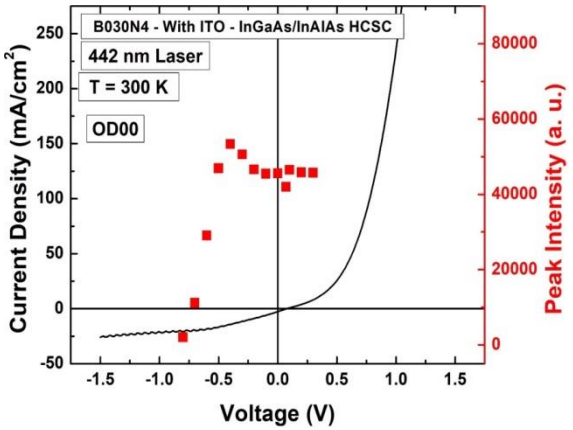






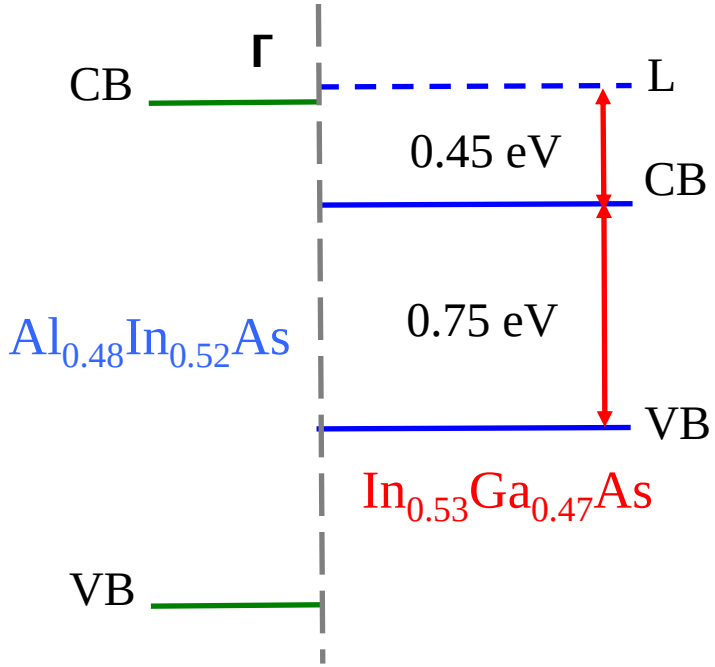


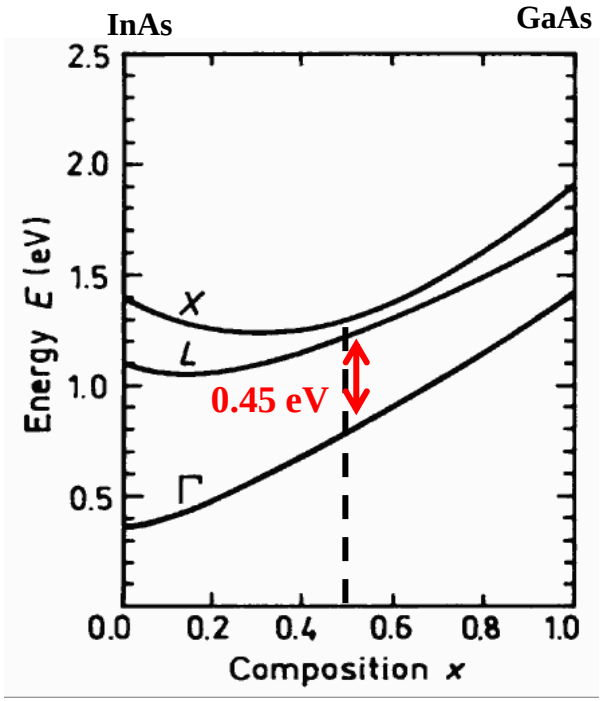




Temperature and intensity dependent barrier to minority carrier extraction: for both high and low energy photo generated carriers

Role of Valley Degeneracy at Absorber/Barrier Interface

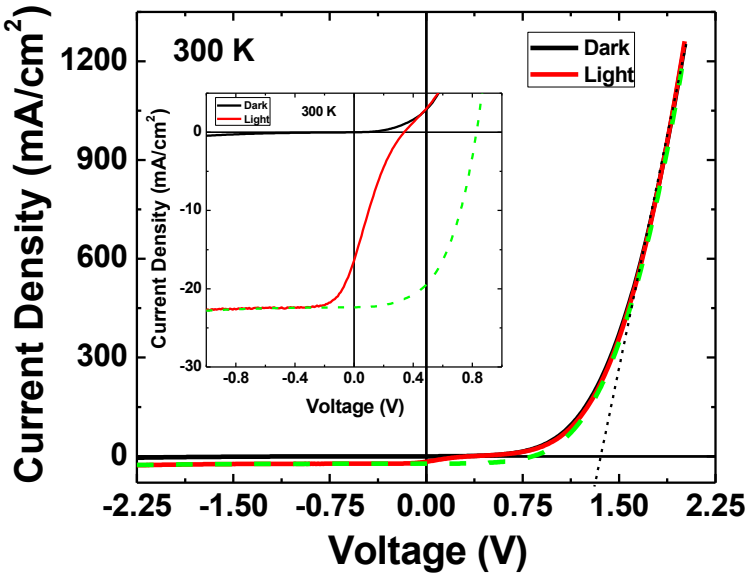




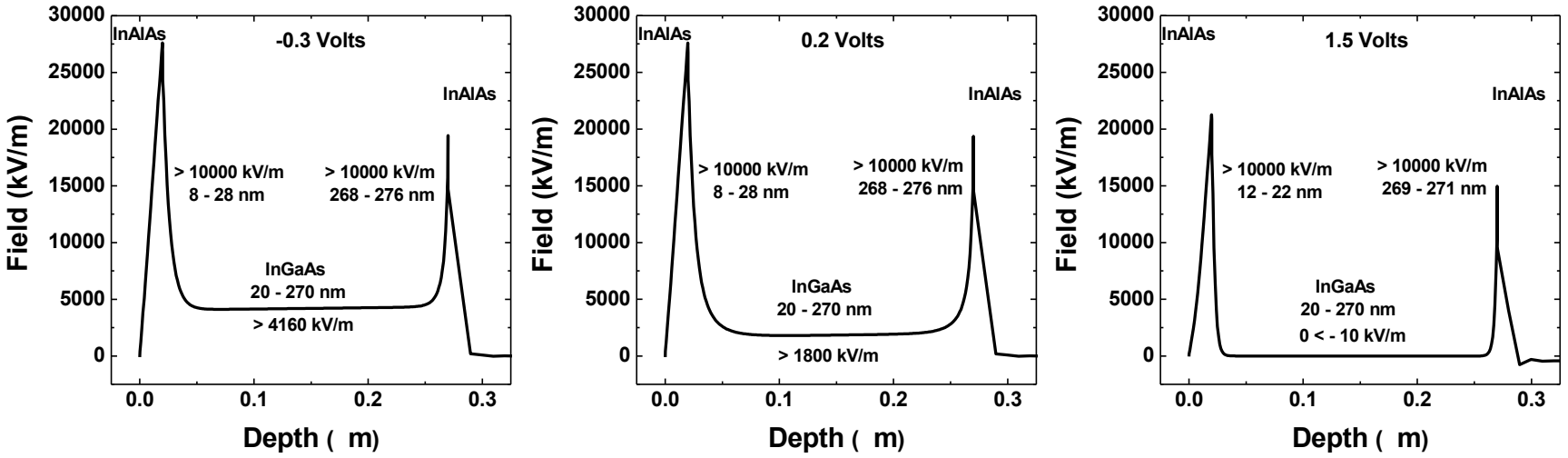
Porod and Ferry (1983)

- Experimental evidence for hot carrier transfer and low energy carrier scattering to upper valleys at low excitation power (1-sun)
- However…… the valley degeneracy mismatch at the InGaAs (*L*) – AlInAs (*Γ*) interface inhibits fast carrier extraction

Potential & Challenges:

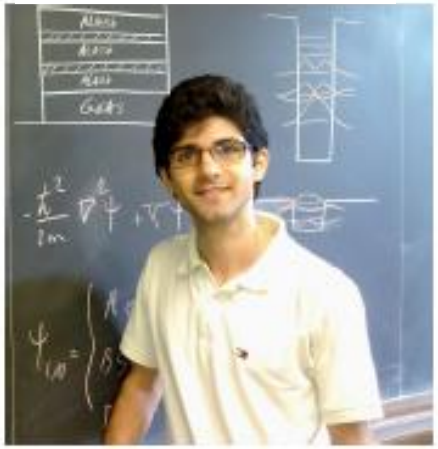


- PL indicates presence of hot carriers at low excitation powers with both VIS and IR excitation
- Operating voltages demonstrated in excess of InGaAs bandgap – hot carriers
- Extraction of current still limited by Valley degeneracy between absorber and barrier: *non-traditional systems and/or more complex quaternaries*
- *Electric field in active region/at interface must be retained under operation: some evidence but novel designs required*



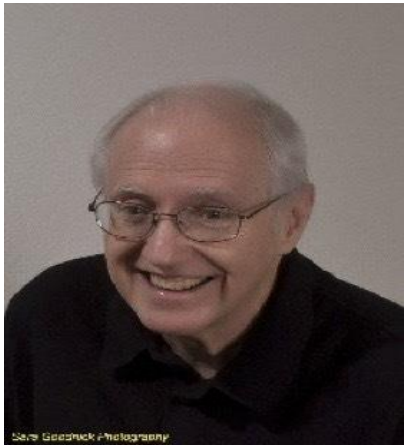
Acknowledgements

Hamidreza Esmaielpour

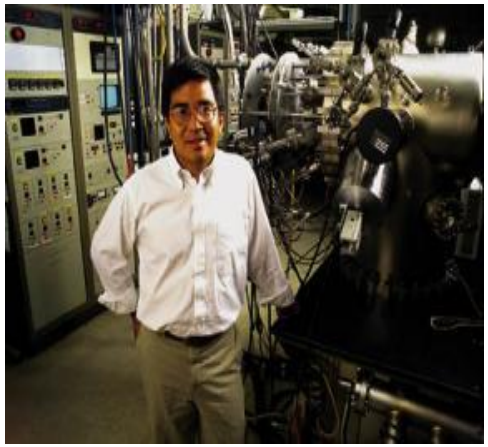


Vincent Whiteside

Dave Ferry



Mike Santos



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ECCS # 1610062

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V. R. Whiteside *et al*. Semi. Sci. Tech. 34, 025005 (2019)

V. R. Whiteside *et al.* Semi. Sci. Tech. InAs/AlAsSb *accepted* (2019)

H. Esmaielpour, V. R. Whiteside *et al*. InGaAs/AlInAs *coming soon….*

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