Control of hot carrier thermalization in type-II quantum wells: a route to practical hot carrier solar cells

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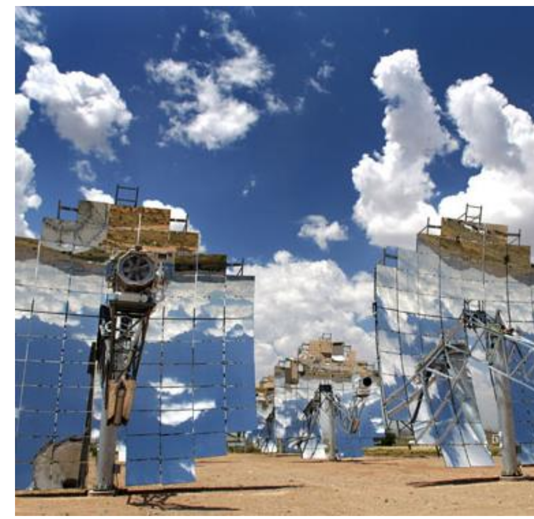
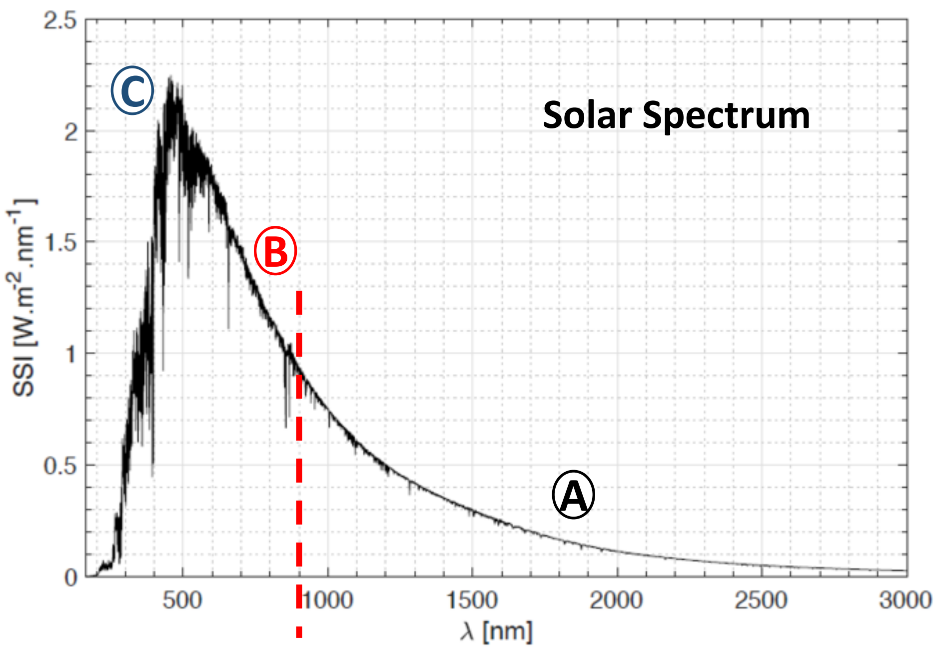
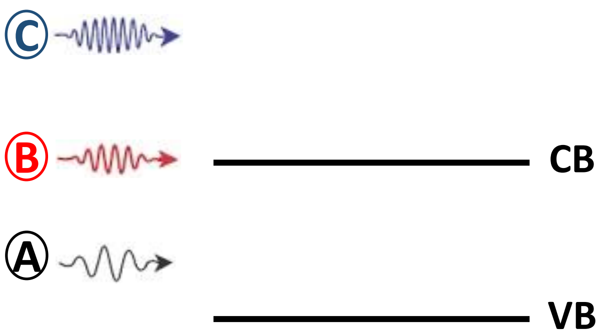


- Introduction: Hot Carrier Solar Cells
- InAs/$AlAs_xSb_{1-x}$ QWs and Optical Properties
- Hot Carrier Temperatures and Thermalization Coefficient
- Dynamics of Hot Carriers
- DFT Calculations and Raman Spectroscopy
- Electrical Characterization: Hot Carrier p-i-n diode

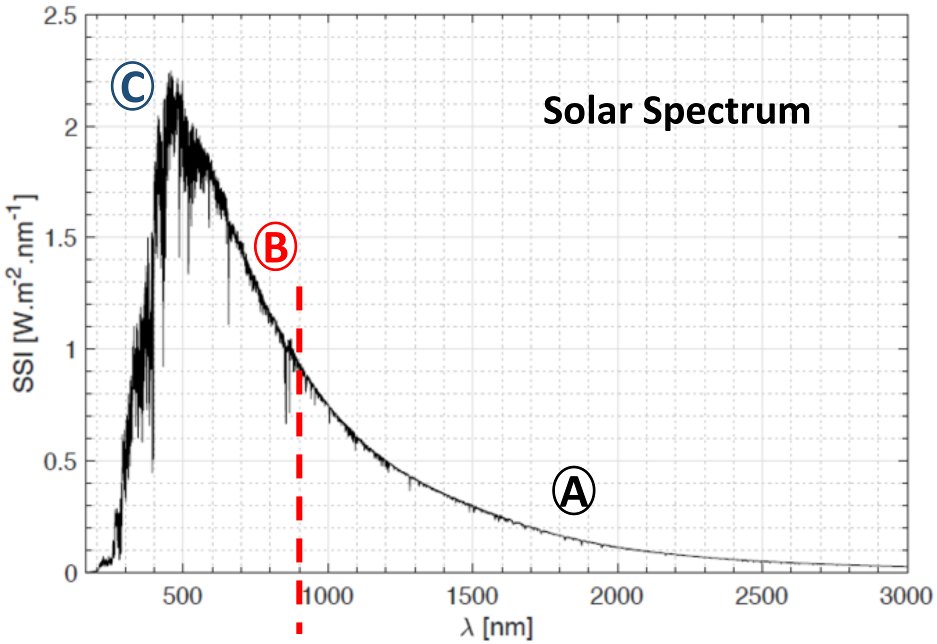
Introduction: Hot Carrier Solar cell



https://www.esa.int/spaceinimages/Images/2017/12/Solar_spectrum



Introduction: Hot Carrier Solar cell



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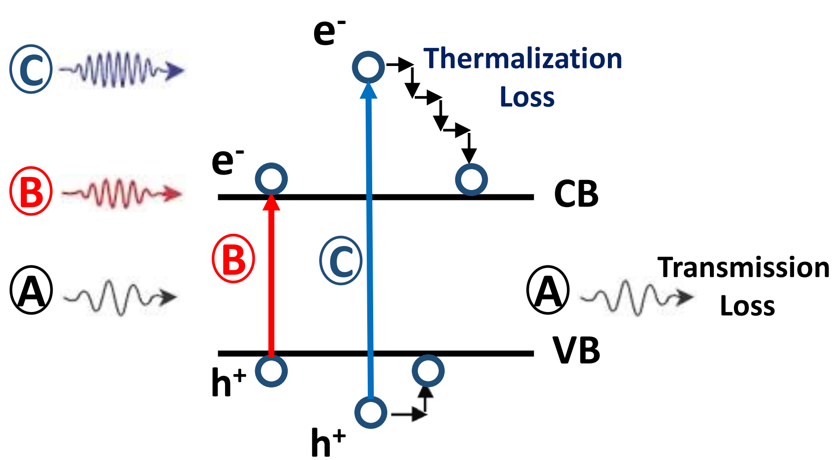
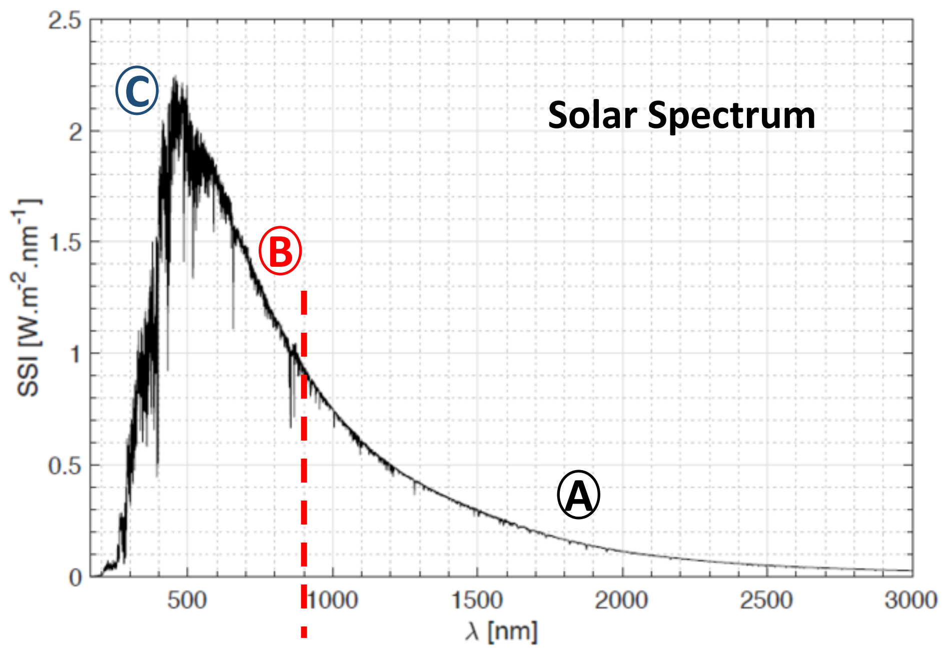


- Maximum Theoretical Conversion Efficiency:
  33% No-Concentration (1 sun)
  (Shockley-Queisser Limit)

Introduction: Hot Carrier Solar cell



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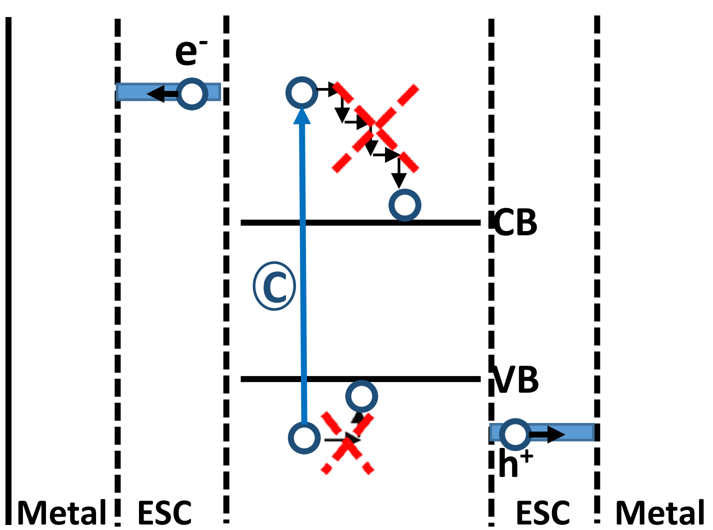


- **Maximum Theoretical Conversion Efficiency:**
  68% No-Concentration (1 sun)

Determination of carrier temperature

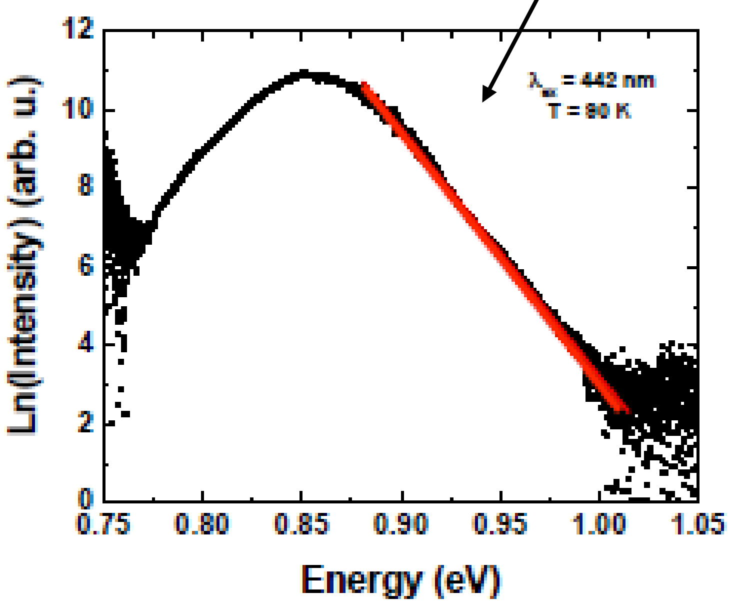
- **Linear fit**

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

Generalized Planck's law

- 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)

$$\boldsymbol{ln\,(I_{pl}(E)) \propto \left(-\frac{E}{k_B T_{eh}}\right)}$$



Related Research:

- A. Le Bris, L. Lombez, J. F. Guillemoles, *Energy & Environmental Science*, *5*(3), 6225-6232 (2012).
- G. Conibeer, N. J. Ekins-Daukes, J. F. Guillemoles, D. Kőnig, M. Green, *Solar Energy Materials and Solar Cells*, *93*(6-7), 713-719 (2009).
- L. C. Hirst, M. Sugiyama, N. J. Ekins-Daukes, *IEEE Journal of Photovoltaics*, *4*(1), 244-252 (2014).

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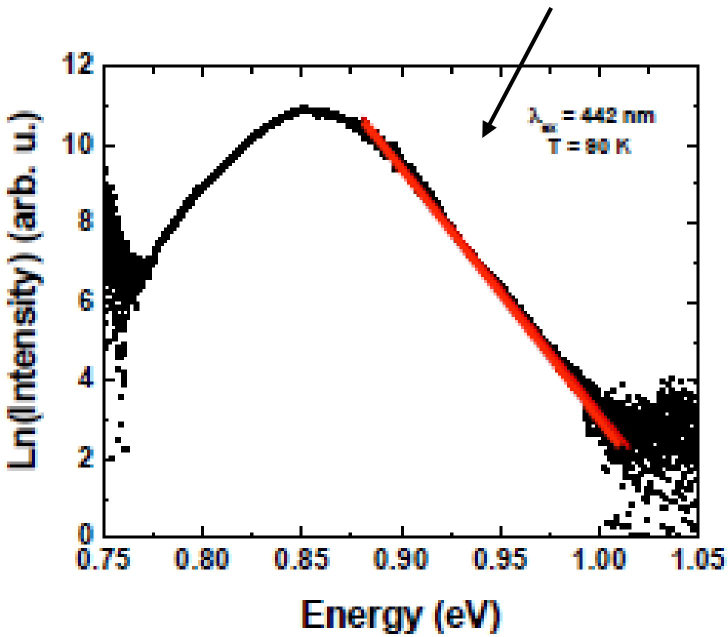
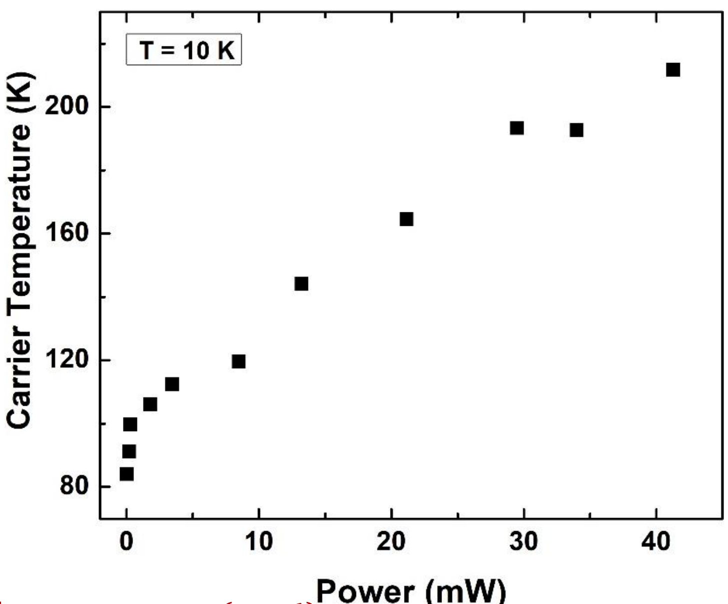
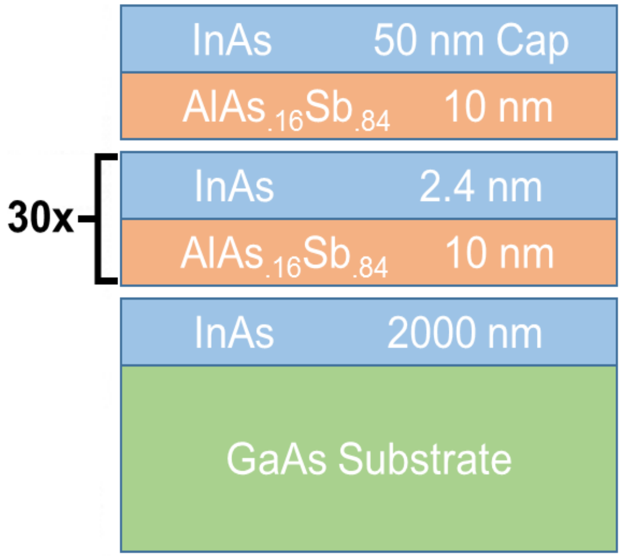
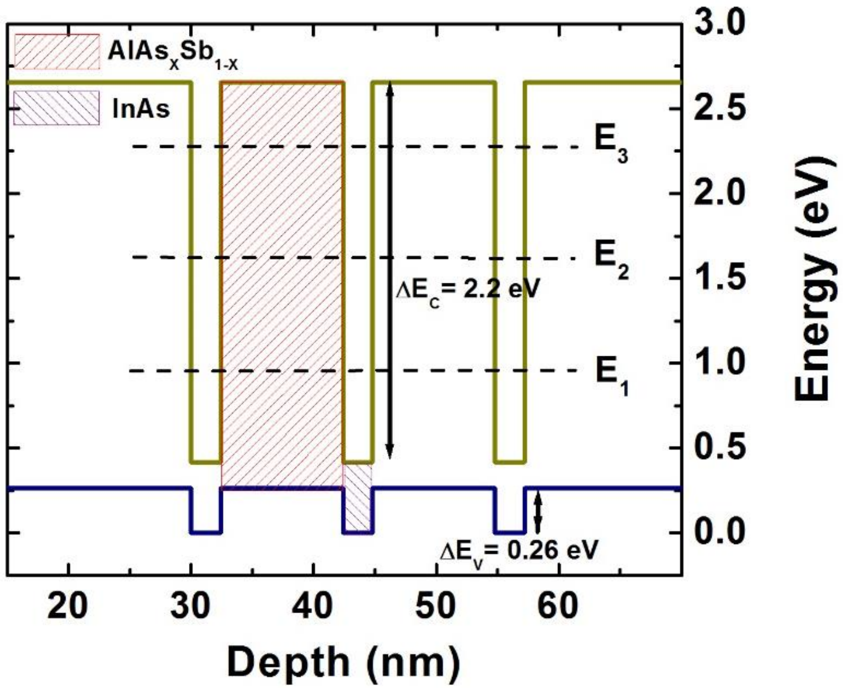




H. Esmaielpour, I. R. Sellers, *et al.* Prog. Photovolt: Res. Appl., 24: 591–599 (2016).

Type-II $InAs/AlAs_{0.16}Sb_{0.84}$ quantum well structure

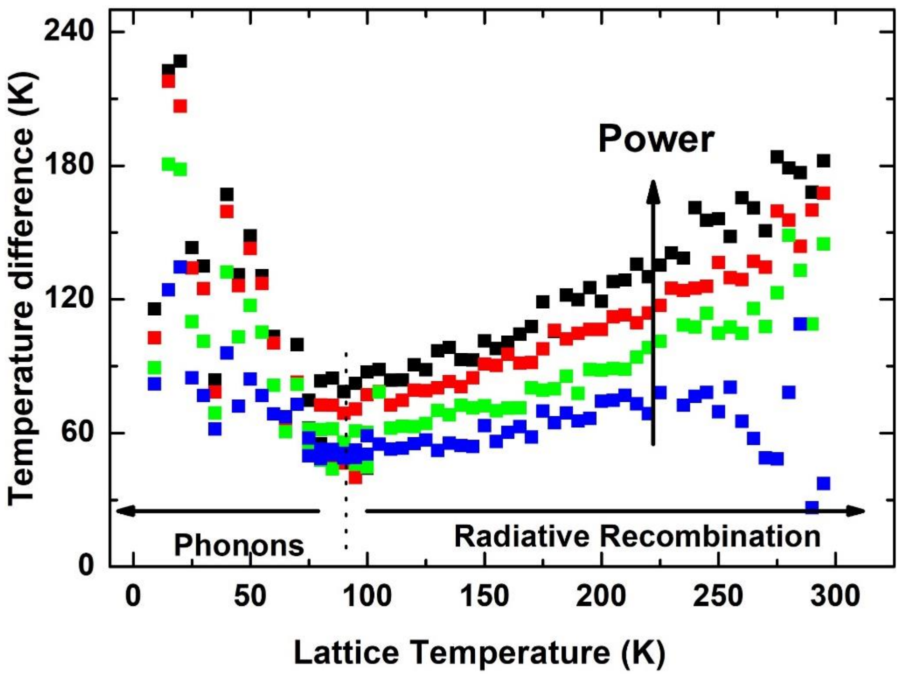


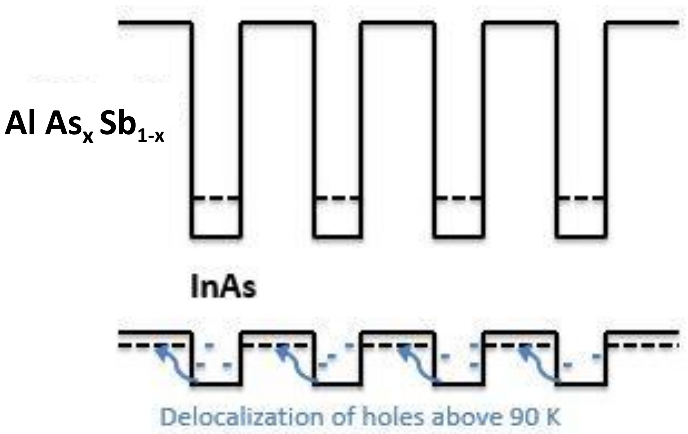


- "Deep" QW in the conduction band
- *Quasi*-type I structure
- Low quantum confinement in valence band
- Potential of creating resonant tunneling through a superlattice structure

J. Tang, H. Esmaielpour *et al.* Appl. Phys. Lett. 106, 061902 (2015)

Analysis of Hot Carriers and their temperature (T_{eh})





- Below 90 K, phonon mediated thermalization of hot carriers due to localized states at the interface is dominant.
- Above 90 K, radiative recombination of spatially separated photogenerated charges in type-II band alignment is the dominant mechanism which creates robust hot carrier effect at elevated temperatures.

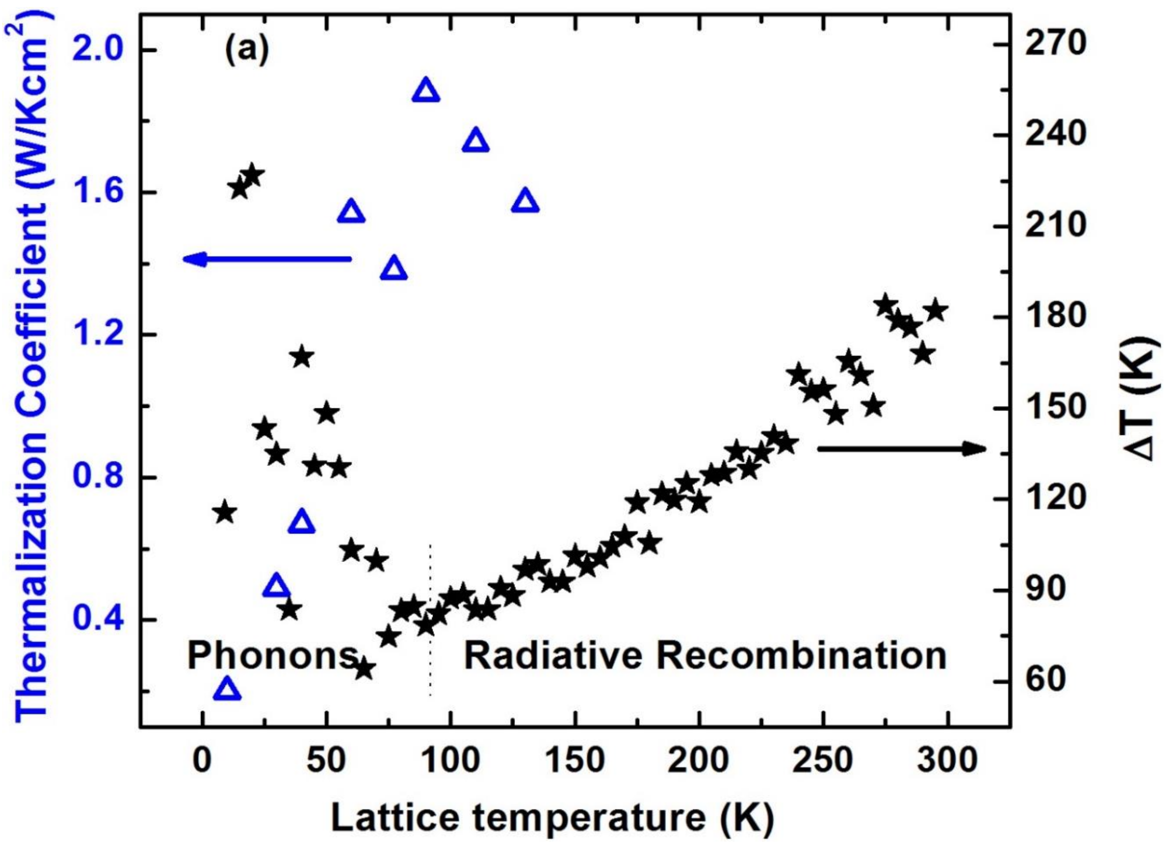
J. Tang, H. Esmaielpour *et al.* Appl. Phys. Lett. 106, 061902 (2015)

Thermalization coefficient in InAs/AlAsSb QWs

$$P_{abs} = P_{th} = Q(T_{eh} - T)\exp\left(-\frac{h\nu_{LO}}{k_B T_{eh}}\right)$$

Q: Thermalization coefficient

Le Bris, A., *et al.* Energy & Environmental Science 5.3 (2012): 6225-6232.



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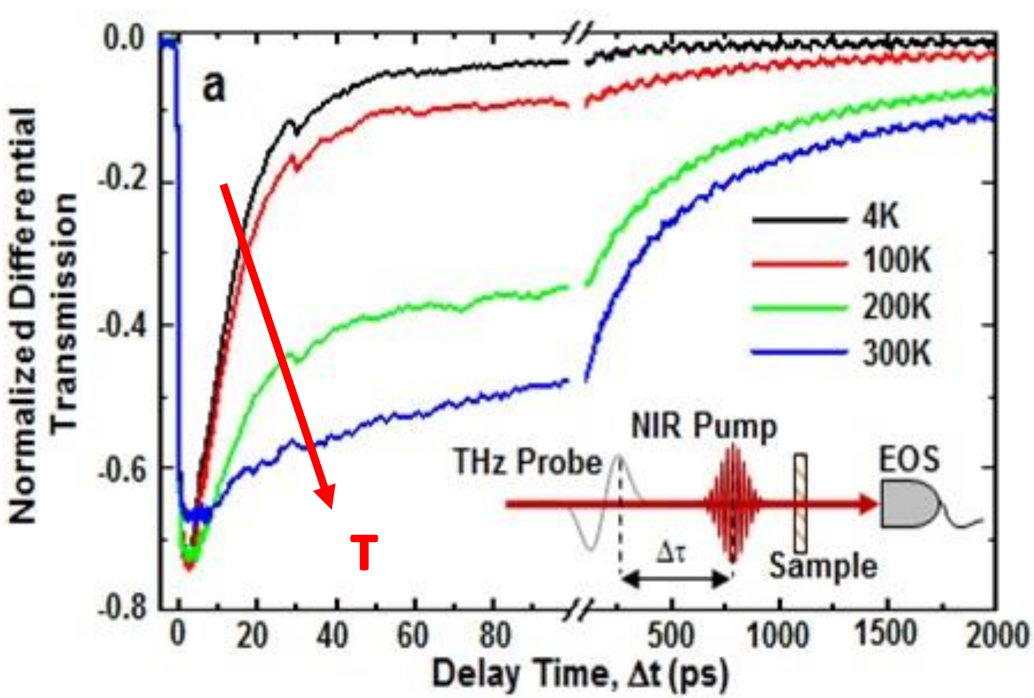
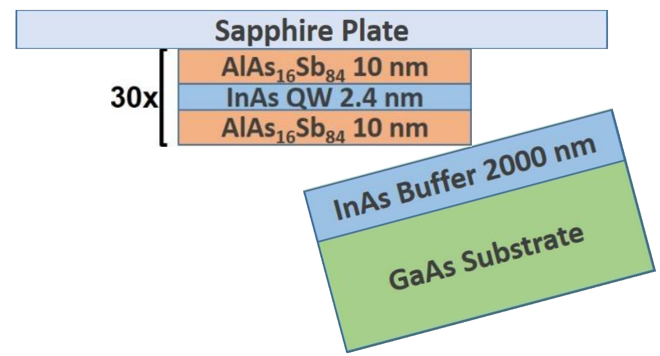
Time Domain THz Spectroscopy: AC Photoconductivity



Processed Sample for Ultra-fast Transient Absorption Spectroscopy



$$\Delta E(t)/E = \sum_{i=1}^{3} A_i \, exp[-(t-t_0)/\tau_i]$$

E: *THz Electric Fields*
A_i: *Normalized Amplitude*
τ_i: *Decay Time*

West Virginia University ***H. P. Piyathilaka, A. D. Bristow***

H. Esmaielpour, I. R. Sellers, *et al*. Scientific Reports (under review).

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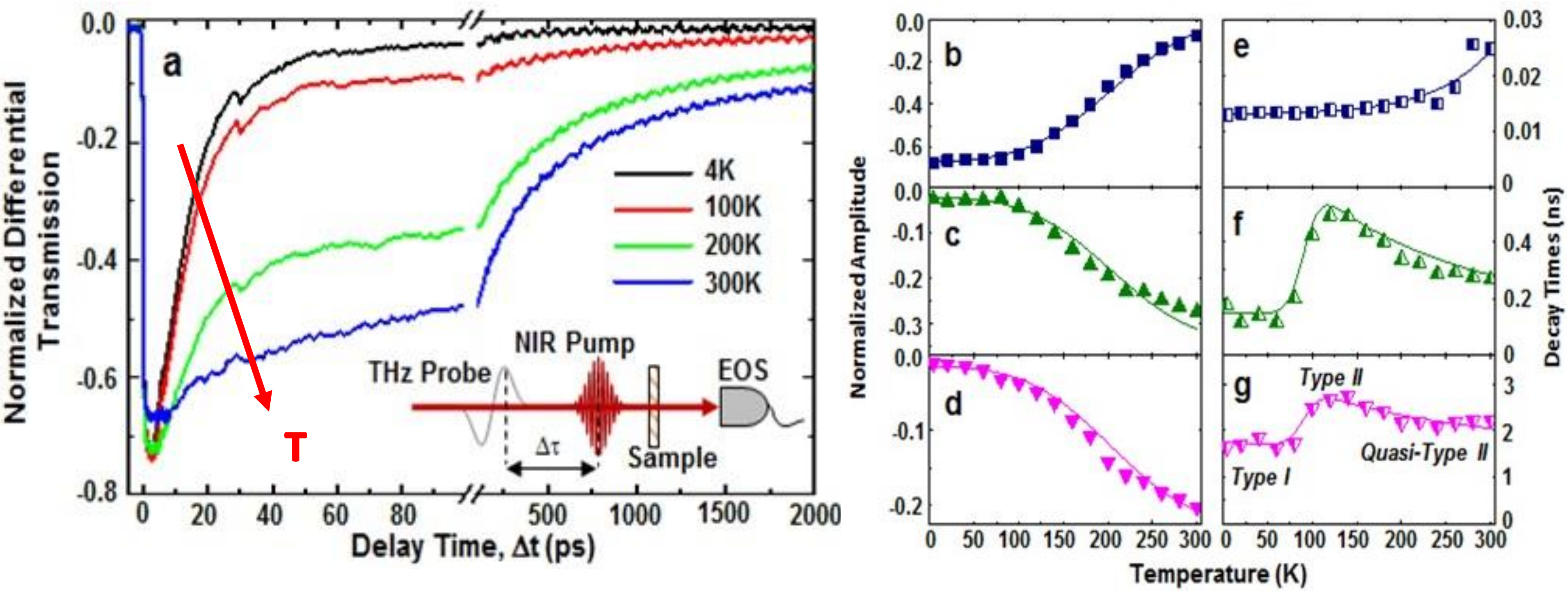

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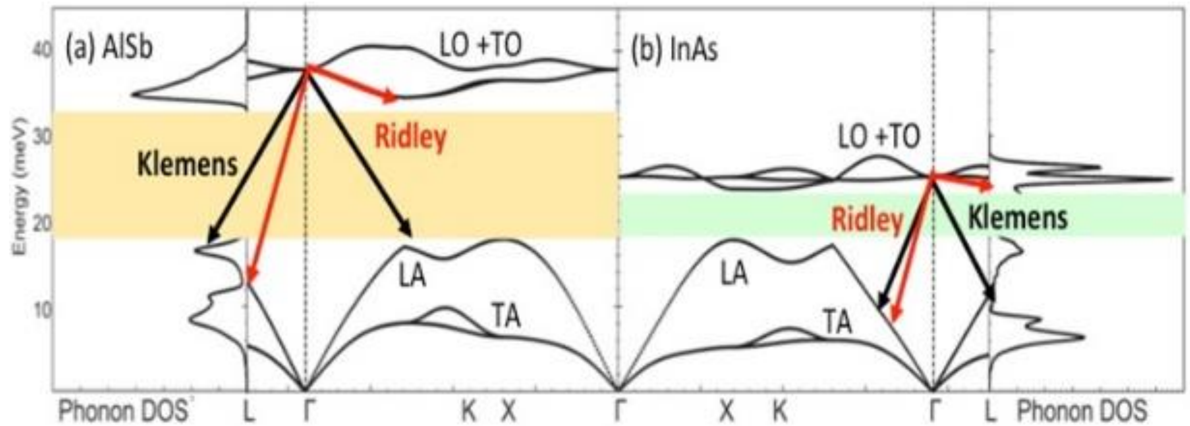
H. Esmaielpour, I. R. Sellers, *et al.* Scientific Reports (under review).

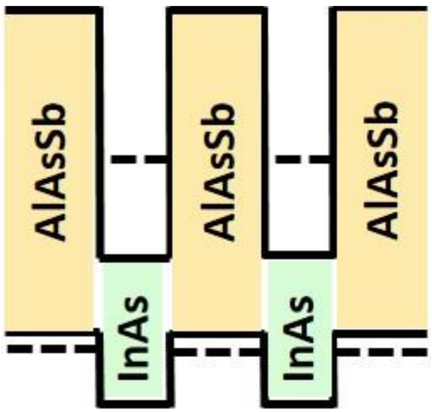
V. R. Whiteside, H. Esmaielpour, I. R. Sellers, *et al.* Semiconductor Science and Technology (under review).

Phononic Properties of InAs/AlAsSb QW Structure

- DFT Calculations



- ❖ Large optical phonon band gap for AlSb sample due to a large difference between cation and anion mass.
- ❖ Large difference between optic and acoustic phonon energy for AlSb ($\hbar\omega LO/\hbar\omega LA \sim 1.9$) (see tan shaded region) and small difference between optic and acoustic phonon energy ($\hbar\omega LO/\hbar\omega LA \sim 1.1$) for InAs (see green shaded region)

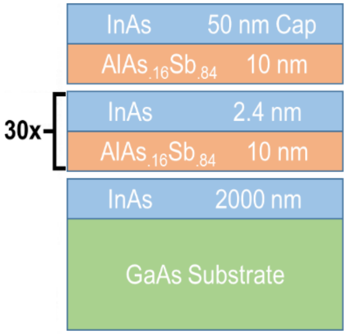


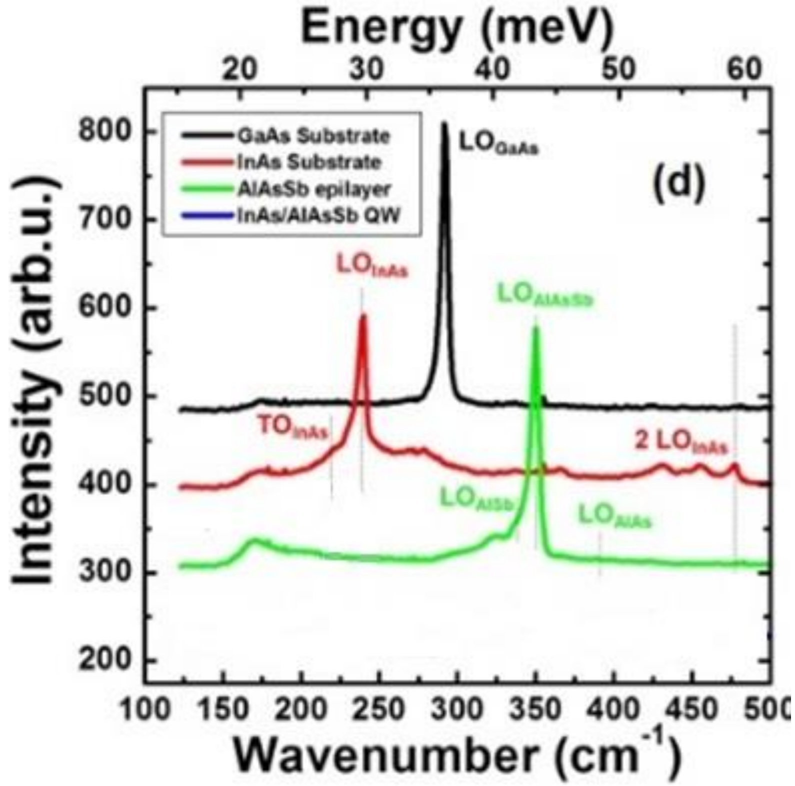
B. Wang

H. Esmaielpour, I. R. Sellers, *et al.* Scientific Reports (under review).

Phononic Properties of InAs/AlAsSb QW Structure

- **Raman Spectroscopy**





E. Adcock-Smith,
K. P. Roberts

H. Esmaielpour, I. R. Sellers, *et al.* Scientific Reports (under review).

Phononic Properties of InAs/AlAsSb QW Structure

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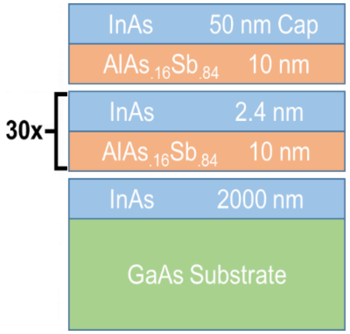
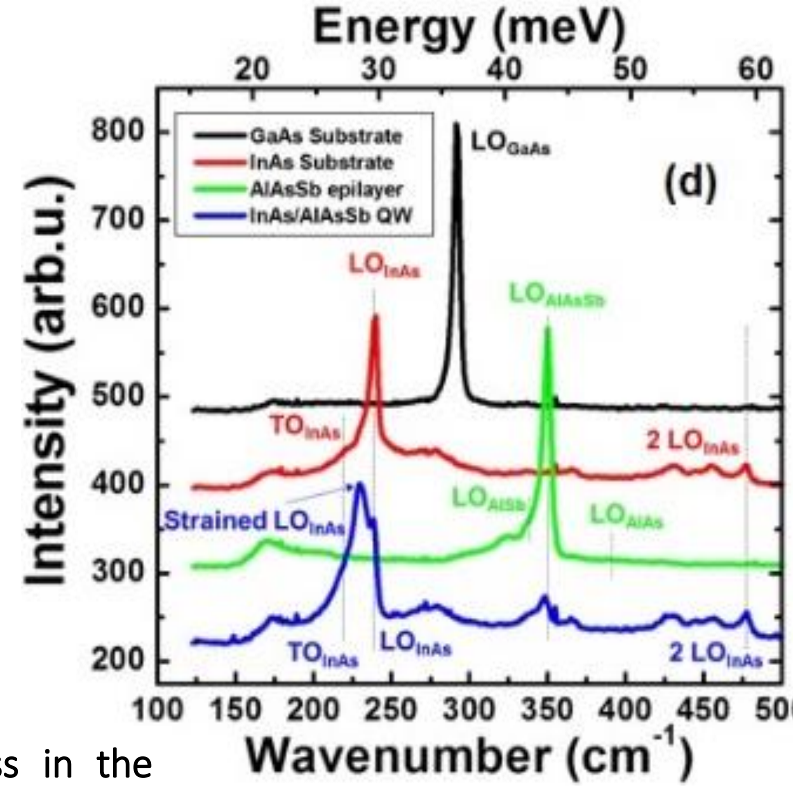
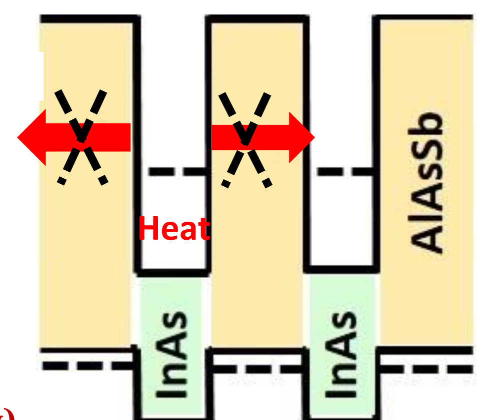




❖ Limited contribution of phonon process in the barriers (AlAsSb) in carrier thermalization.

❖ Strong confinement of hot electron-phonon process within the QWs.

❖ Up-conversion of LA phonons to LO phonons and re-heating and stabilizing hot electron distribution within the InAs QW.



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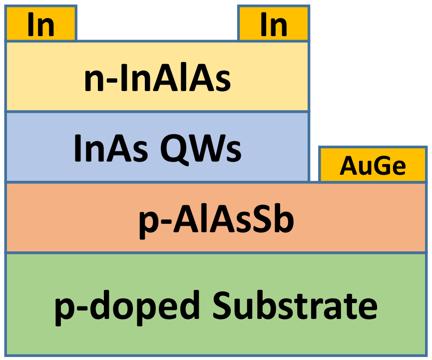
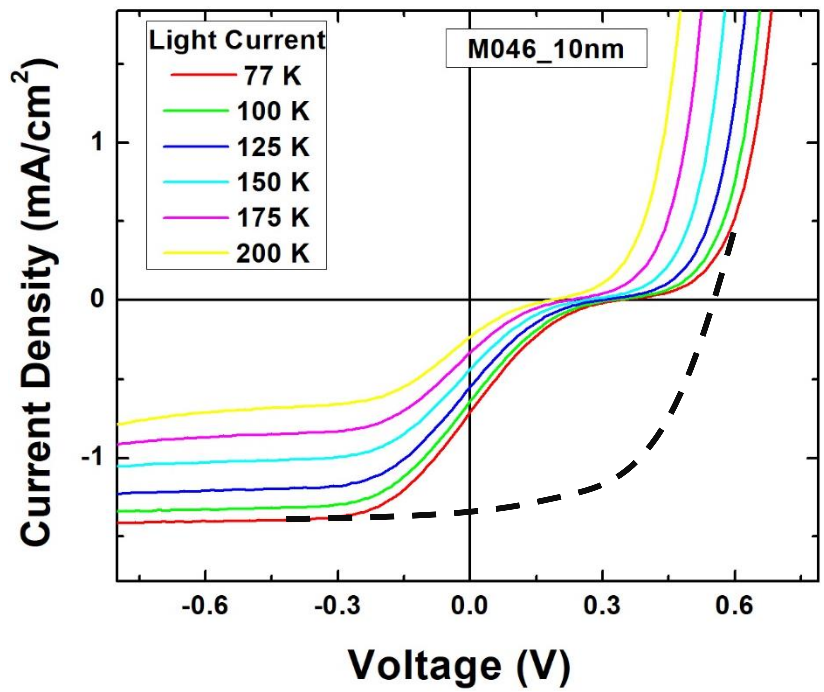
Electrical characterization: Hot carrier p-i-n diode

- I-V measurements as a function of barrier thickness



Related Research:

- L. C. Hirst, R. J. Walters, M. F. Führer, N. J. Ekins-Daukes, *Applied Physics Letters*, *104*(23), 231115, (2014).

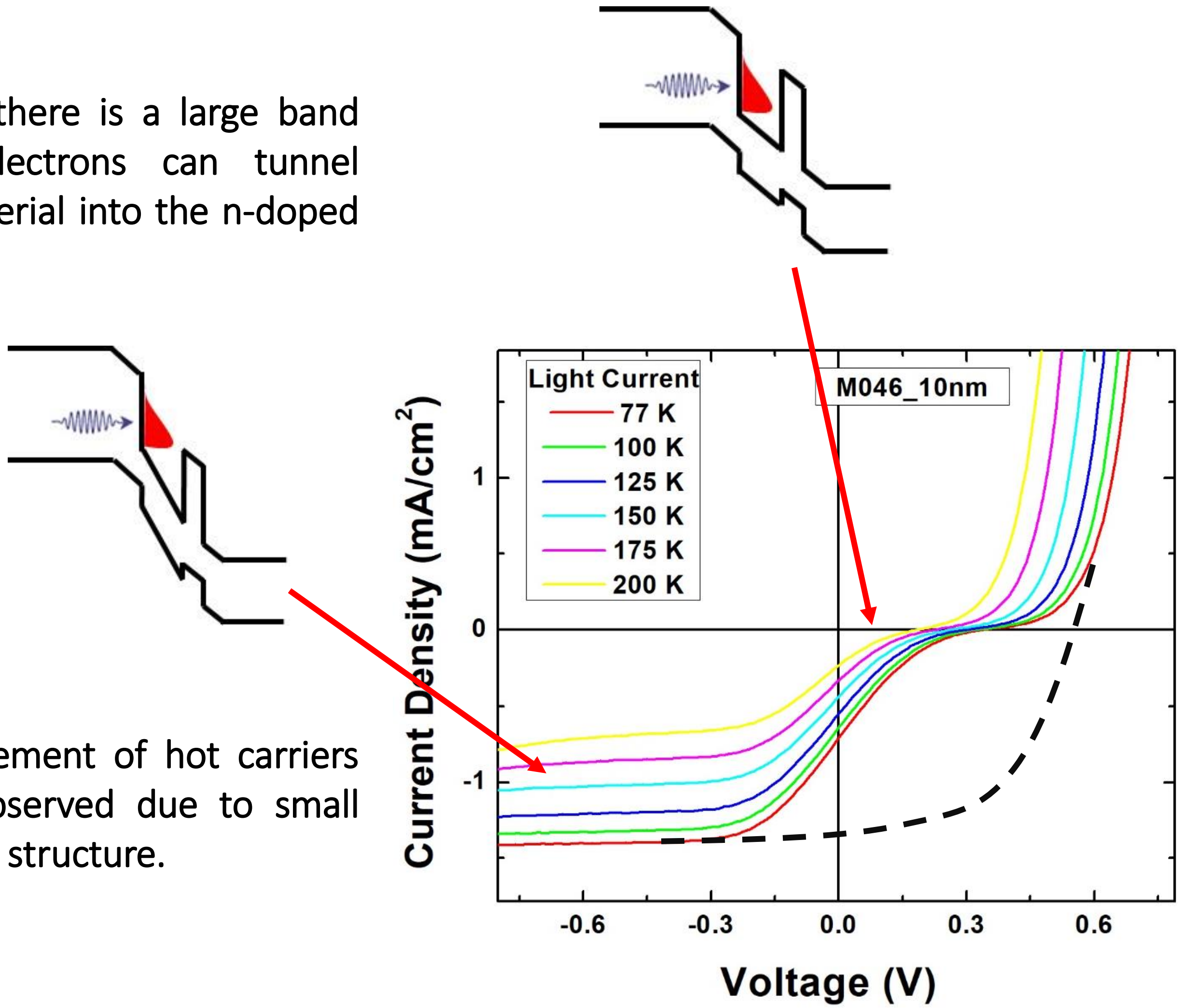


Electrical characterization: Hot carrier p-i-n diode

- **I-V measurements as a function of barrier thickness**

❖ At reverse bias where there is a large band bending, generated electrons can tunnel through the barrier material into the n-doped region.

❖ At forward bias, confinement of hot carriers within the QW was observed due to small band bending of the QW structure.

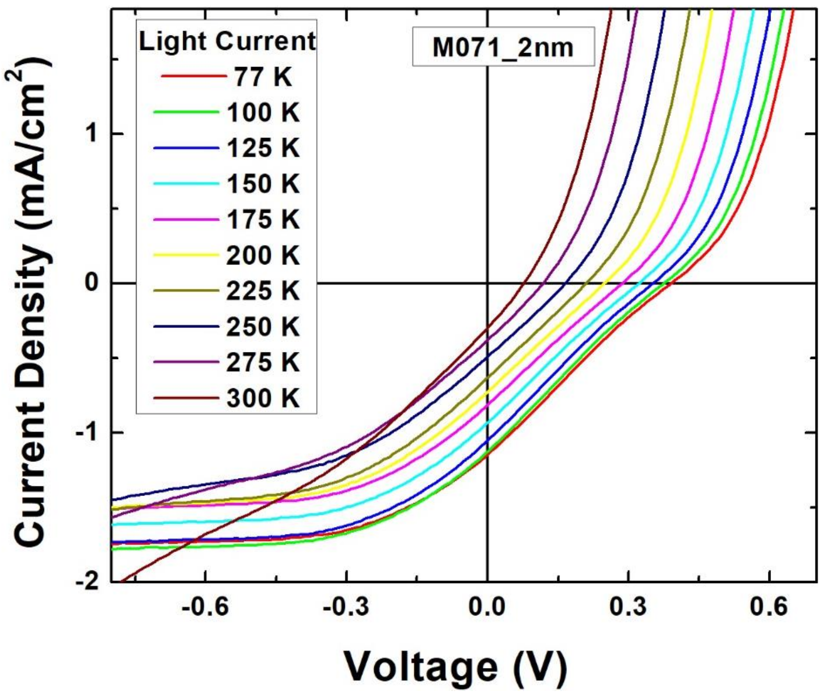


Electrical characterization: Hot carrier p-i-n diode

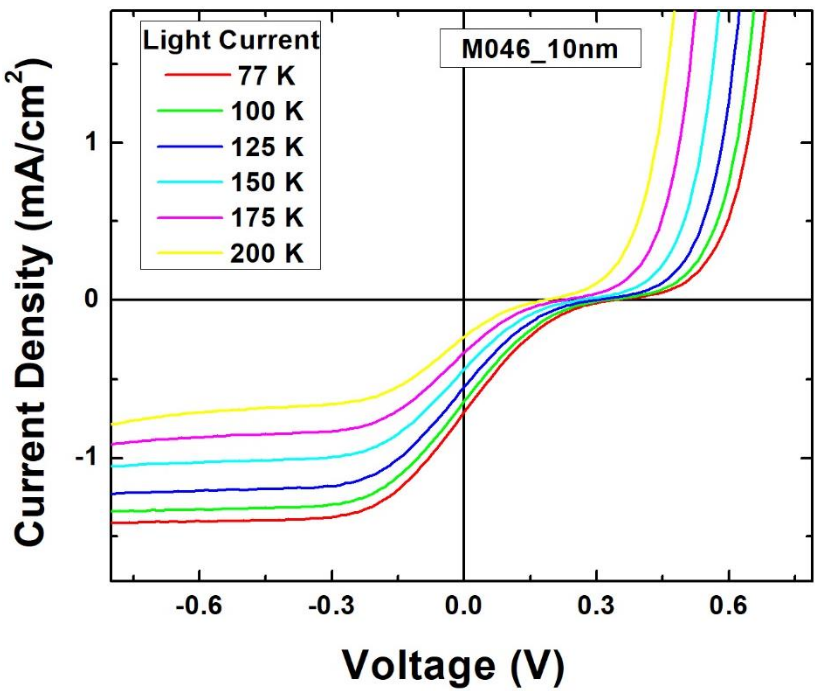
- I-V measurements as a function of barrier thickness

❖ Smaller carrier confinement within the QW is observed for the p-i-n device with a thinner barrier material.

2 nm barrier p-i-n diode

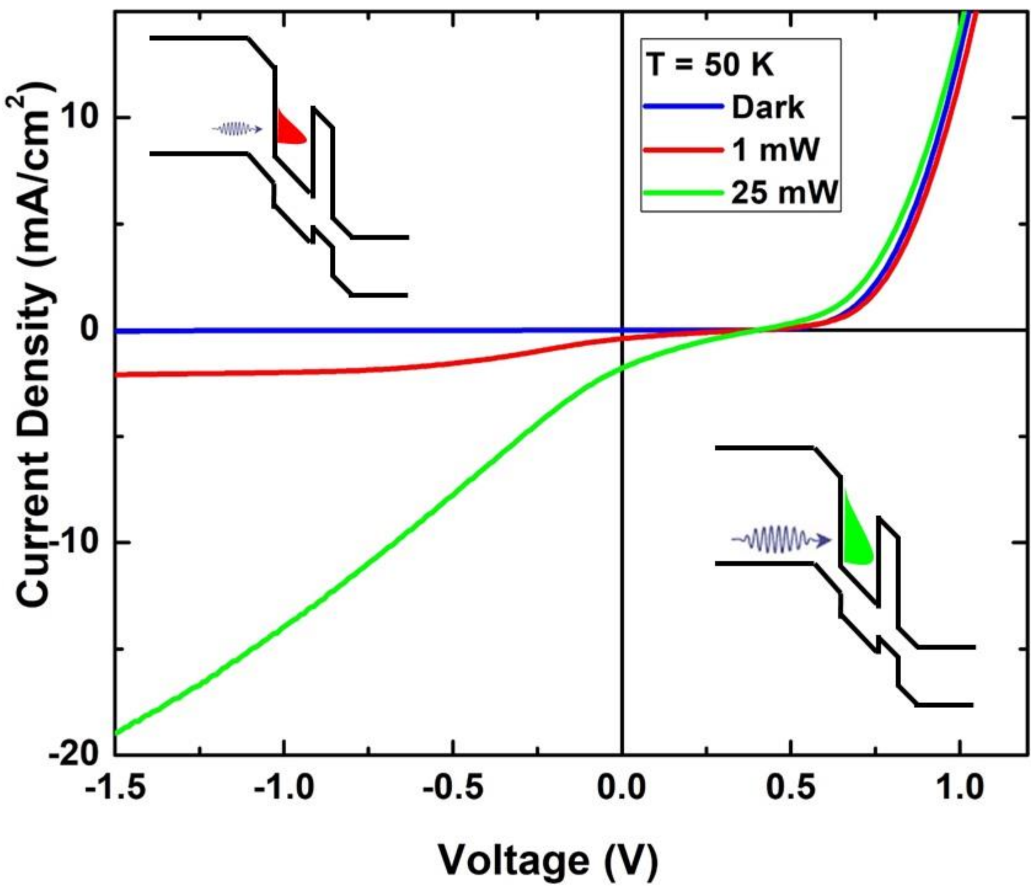


10 nm barrier p-i-n diode



Electrical characterization: Hot carrier p-i-n diode

- **Power dependence**



❖ By increasing the barrier thickness, less amount of current can escape from the confinement of the QW.

❖ As power increases, more hot electrons can escape from the QW.

Summary

- $InAs/Al_xAs_{1-x}Sb$ quantum wells offer potential as active absorber in hot carrier solar cells.
- Thermalization factor analysis appears unsuitable for the proposed mechanism at higher temperatures.
- Evidence of state filling in the valence band has been observed.
- Carrier temperatures and chemical potentials for generated electrons and holes have been found using the non-equilibrium generalized Planck's law.
- Tera-hertz time domain spectroscopy (TDS) has been done using a processed sample made of only the InAs MQWs.
- Hot carrier p-i-n diodes have shown the existence of hot carriers confined within the InAs MQWs.

Acknowledgments

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West Virginia University

U.S. NAVAL RESEARCH LABORATORY

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THE UNIVERSITY of TULSA